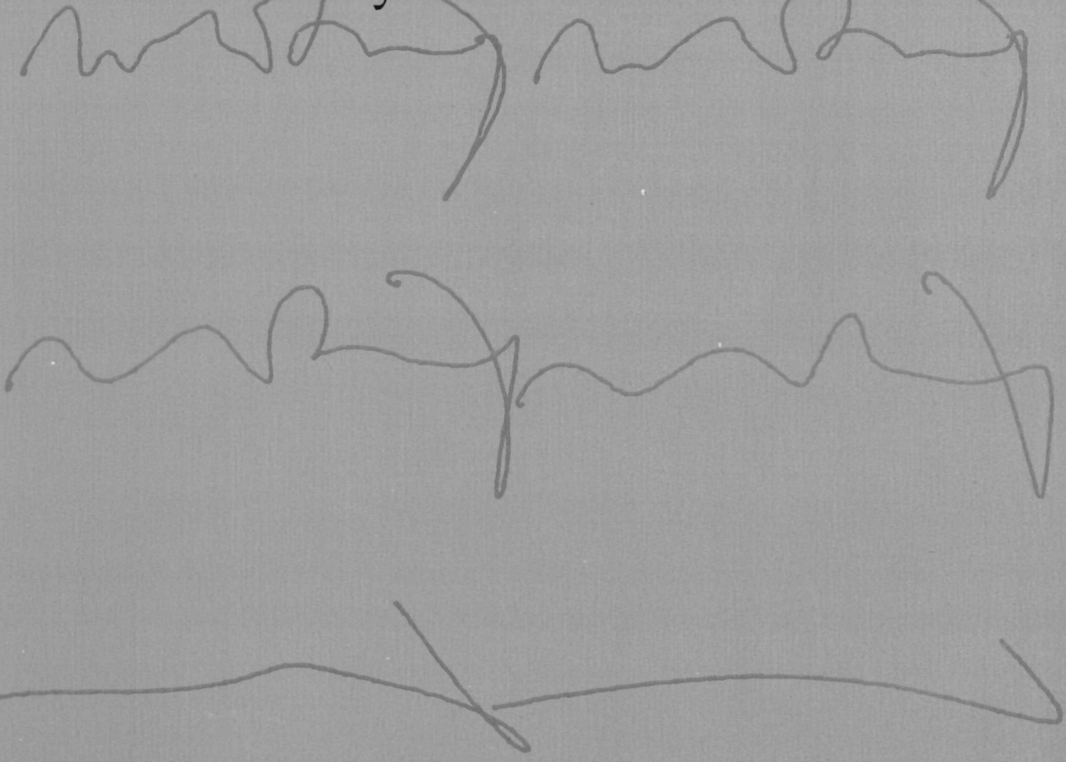
Hans - Leo Teulings

Handwriting movement Control

Research into different levels of the motor system



Handwriting-Movement Control:

Research into Different Levels of the Motor System

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Research into Different Levels of the Motor System

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Contents

Preface

The present thesis deals with the motor-control aspects of handwriting. Chapter 1 places handwriting movements in the context of the rich variety of movements that can be executed by the human movement system. The research within the framework of this dissertation is arranged according to a three-levels model of handwriting-movement control. The levels, which will be introduced in this chapter, range from abstract long-term memory representation, via memory retrieval, to the concrete execution by joints and muscles. The first chapter is concluded by an abstract of the present dissertation. The model's levels are elaborated in Chapters 2, 3, and 4, respectively. Finally, Chapter 5 describes the processing of the recorded handwriting movements and some properties of handwriting considered as a two-dimensional signal. Each of these chapters opens with a brief introduction, providing a connection with the previous chapter. The body of each of the latter four chapters consists of a publication in facsimile (except the one in Chapter 4, which has not yet appeared in print). These chapters are concluded by a discussion of the publication in light of more recent developments. The literature references belonging to all these texts, which have not been previously published, are presented at the end of Chapter 5. The last part of the dissertation is formed by summaries in English and Dutch and by the author's curriculum vitae.

CHAPTER 1. OVERVIEW

Handwriting as a Specific Category of Movements

The study of human movements is relevant because it is the motor system which controls a large variety of vital functions like human information output, displacement of the human body, postural movements, or manipulative movements. The motor system has to cope with a large number of complicating factors: movements may be specified in space, time, and force domains; posture and balance have to be maintained; proprioceptive and visual feedback have to be processed; gravitational, frictional, viscous, and inertial forces have to be taken into account; and, most of the time, a large number of limbs, joints and muscles are involved. A unified motor theory would be the ideal but this is not realistic given the present state of the art. Therefore, many motor theories are based on isolated movements with restricted degrees of freedom. If one wishes to investigate real-life and 'ecologically valid' movements one should choose a category of movement which has some restrictions by virtue of its nature. Handwriting movements are an example of such a category of movement: they are defined in the two-dimensional spatial domain and they require relatively little visual or proprioceptive feedback, coordination or anticipation. As a result, they constitute a category of ecologically valid movements, a category that is highly suitable for research, as may be illustrated by the number of theses on this subject that have been completed recently (e.g., Dooijes, 1984; Maarse, 1987; Blöte, 1988). Moreover, the motor aspects of handwriting have recently received considerable attention in an international and multidisciplinary setting (e.g., Thomassen et al., 1984; Kao et al., 1986; Plamondon et al., 1988). The present thesis is concerned with the movement-control aspects of adult, practiced handwriting. The purpose of the present first chapter is to specify the category of handwriting movements investigated in this thesis, to introduce a macroscopic model, to locate the other chapters in the context of the latter model and, finally, to integrate the results of this thesis.

We investigated handwriting from the experimental psychology point of view. Handwriting may also be considered from a typically educational, or remedial-teaching angle. Such a perspective involves aspects related to motor development, motor learning, handwriting instruction, and diagnosis and treatement of dysfunctions (e.g., Blöte, 1988; Meulenbroek & Van Galen, 1986; Peck et al., 1980; Thomassen & Teulings, 1983). Although these aspects are relevant, they will not be discussed here. Handwriting can also be studied from a biophysical view-point (e.g., Denier van der Gon & Thuring, 1965) or from that of engineering and robotics (See Plamondon et al., 1988). Results obtained here are often relevant to our research. Finally, since several decades, handwriting production has been studied from the pattern-recognition point of view, in order to achieve the extremely difficult task of automatic cursive-script recognition (e.g., Srihari & Božinović, 1987).

In the present thesis, handwriting is considered a motoric skill. In this context it has a number of specific features, which deserve a brief summing-up. In literate adults, handwriting constitutes a universal, highly trained human skill with writer-specific characteristics. The movements are generated top-down from higher-order, well-defined linguistic representations, at the level of words. As their final purpose is to produce sequences of distinct, i.e., legible letter shapes, the movements are specified in the spatial rather than in the temporal domain. The shapes are produced by moving the tip of a pen on and above a two-dimensional writing surface. The pen-tip position can be recorded virtually continuously by means of available computer devices (electronic pen and digitizer). The pen tip makes rapid, multi-phasic sequences of ballistic movements, allowing the estimation of segmentation points. The performance of handwriting is largely independent upon internal or external feedback. The rapid movements are, to a large extent, the result of muscle contractions and relatively uninfluenced by inertial, frictional or gravitational forces. They employ no high force levels and cause practically no muscular fatiguing effects. They are performed with 'small amplitudes', thus requiring no extreme joint flexions. They are produced by a limbs-in-series movement, which does not require the coordination of independent limbs as in a bimanual task, although thumb and opposing fingers may to some extent move independently.

Handwriting is also a graphic skill. However, not all graphic skills and their motor requirements will be considered in this thesis. Skills like drawing, painting, calligraphy (which require extensive visual feedback), or scribbling (which does not require a higher-order control schema) will not be considered in this thesis. On the other hand, the field we investigate does include skills such as shorthand - using a more parsimonious character standard, which departs from the conventional, basic letter shapes - and also slightly more remote skills like typewriting, speech and rapid arm movements. The writing patterns that we shall investigate in this thesis cover the range from normal cursive handwriting to simple, rapid zig-zag patterns.

Handwriting is also a linguistic skill, but as such, it is not considered in this thesis. However, it may be useful to locate the related linguistic skills of writing and spelling. Writing is the generation of ideas and their subsequent phrasing according to lexical and syntactical rules. Spelling is the generation of the correct sequences of characters according to orthographical rules. In the present context, we wish to reserve the term handwriting for the preparation and generation of the movements that result in sequences of cursive or handprinted characters. This includes the choice of the style of the characters, depending upon context or instruction.

A Macroscopic Model Encompassing the Handwriting Motor System

The language perception and production model by Ellis (1982) offers the right scope in order to locate handwriting motor control in a sufficiently wide context of human behavior. Moreover, it illustrates the general theoretical framework providing the context for the present research into different levels of the motor system. This model comprises two parallel input paths, one for spoken and one for written information, leading to a central 'cognitive system'. It also has two parallel output paths, one for speech and one for handwriting. The handwriting-output path contains a sequence of components. The existence and function of each component has been hypothesized by Ellis on the basis of *slips of the pen* or disruptions due to neural pathologies. The first component to be considered here is the *graphemic buffer* where the correct spelling of the word to be written is available in terms of graphemic codes. This buffer's contents are sent to an *allographic long-term store*, where for each grapheme the allographic code can be retrieved, which is subsequently stored in an *allographic buffer*. The allographic code describes the shape of a particular version of a grapheme (but not its sequence of strokes). This buffer's contents are sent to a *graphic motor-pattern store*, where the graphic motor pattern can be retrieved, which is subsequently stored in a *graphic motor-pattern buffer* until execution actually begins. Basing himself on Van Galen (1980), Ellis assumes that the graphic motor pattern prescribes the sequence of strokes required to perform the allograph, as practiced during many years of handwriting experience. Finally, the retrieved information is sent to a *neuro-muscular execution component*, which produces the graphs, i.e., the series of uniquely realized allographs.

Although a model of the latter kind, consisting of a set of sequential components, is not the most fashionable, it is certainly a convenient model. Such a model is appropriate to the extent that feedback loops between components are not essential. Although Ellis included feedback loops in his model, they play a minor role in overlearned handwriting movements under stable and predictable execution conditions. Considering the rate of movement production, one may assume that proprioceptive feedback processing is unlikely during ballistic strokes, which have durations as short as 100 ms (e.g., Wadman et al., 1979, 1980). Visual feedback plays rather a monitoring role at the multistroke level than at the stroke level (e.g., Denier van der Gon & Thuring, 1965; Pick & Teulings, 1983; Smyth & Silvers, 1987; Van Galen et al., 1988).

Three Major Levels of the Motor System

In this thesis, the handwriting-motor system will be viewed according to three major levels. These levels are largely compatible with the three lowest components in Ellis' model: long-term motor memory storage (See Chapter 2), long-term memory retrieval (See Chapter 3) and the translation process into muscle commands (See Chapter 4). Finally, Chapter 5 will discuss some of the features of handwriting movement, its recording, and the automatic processing of the resulting signals.

The direct theoretical basis of the present thesis is provided by an influential paper by Van Galen (1980). The latter author in fact distinguished three motor-system components: a motor memory, containing the permanently stored, abstract movement information, a memory-retrieval "stage", and a stage responsible for movement-parameter substitution and muscle innervation. In his general model, Sanders (1983) calls the latter two stages *response choice* and *motor adjustment*, respectively. The separation of the motor system into three components has appeared very useful because many models in motor control, mostly based on other movements than handwriting, focus on only one component. Models focussing on the hypothetical contents of motor memory have been presented by, e.g., Bizzi et al. (1976), Meyer et al. (1982), Schmidt et al. (1979), Shaffer (1981), Viviani and Terzuolo (1980), and Wing and Kristofferson (1973). Models focussing on the retrieval of movement information from memory are proposed by, e.g., Morasso and Mussa Ivaldi (1987), Rosenbaum et al. (1984), Rumelhart and Norman (1982), Schmidt (1975), Sternberg et al. (1978), and Van Galen et al.

(1988). Models focussing on the translation of the abstract movement information into concrete muscle commands are proposed by, e.g., Flash (1987), and Pellionisz and Llinás (1980). Accordingly, in the present thesis the handwriting-motor system will be discussed in terms of these three levels. Finally, a fourth level is formed by the description of the actual pen movements.

1. Long-Term Motor Memory

Handwriting movements cannot be generated without some long-term motor memory containing the essential information on elementary handwriting-movement patterns. The information has been built up during many years of individual writing experience. We suggest that the information is used in the motor programs generating handwriting patterns. A motor program can be defined as an abstract memory structure containing codes capable of being transformed into patterns of movement (Schmidt et al., 1979). Therefore, the stored information leads to specific invariant (e.g., Schmidt et al., 1979) and subject specific (e.g., Maarse et al., 1988b) features. It is a matter of theoretical significance to study what kind of movement information is stored and retrieved. How can we investigate what kind of information is probably stored? One might suppose that each invariant feature found in a set of movement patterns originates from the stored movement information. However, this is a reversed inference which is not necessarily true. The only statement that can be made is that an invariant feature might originate from the information stored. Therefore, additional evidence should be collected, for instance, by showing that an invariant feature varies only when relevant factors are changed and does not vary when irrelevant factors are changed. But probably the most important evidence can be obtained if several related features are compared. For instance, one feature may be invariant solely because this feature is derived from another feature that is even more invariant. In Chapter 2 comparisons of this type will be made. An interesting conclusion was that the relative stroke sizes are more invariant than the relative stroke durations or relative force levels. In fact, the effects of random variations of stroke duration appear to be partly neutralized by the variations of force level, which results in a highly invariant stroke size. This is probably what one would expect in a motor task such as handwriting, the requirements of which are specified in the spatial domain exclusively. The results of such comparisons may be different however, for those categories of movement where the requirements are specified in the time domain (e.g., speech).

2. Memory Retrieval

For the information stored in motor memory to be actually used in a motor program, the appropriate movement information has to be retrieved. However, it seems unlikely that each writing pattern is completely represented in motor memory. It is more likely that only separate strokes or sequences of a few strokes are represented as ready-to-retrieve units of movement. In Chapter 3 a paradigm will be presented, which allows us to discriminate between the hypothesis that a single stroke and the hypothesis that a multi-stroke allograph forms a unit. In the latter chapter it is argued that congruent strokes, i.e., different strokes having the same turning direction, may be represented in motor memory by the same unit. Now, three types of letter pairs can be constructed: pairs of identical allographs, pairs of different allographs but constructed from congruent strokes, and pairs of different allographs constructed from noncongruent strokes. It is then possible to distinguish between these two hypotheses. As the memory-retrieval process takes place whenever a new unit is required, it will mainly affect movement latency (i.e., choice reaction time). It appears that pairs of identical allographs yield short choice-reaction times whereas pairs of different allographs, no matter whether their strokes are congruent or noncongruent, yield long choice-reaction times. These data support the notion of complete allographs being represented as units in a long-term motor memory.

Why is cursive handwriting so fluent, whereas it appears to consist of a sequence of discrete units? It is probably not true that movements are executed immediately after retrieval from motor memory. Instead, the entire movement sequence has to be prepared or organized prior to, or during, movement execution. Various authors suggested mechanisms of preparation. For instance, Sternberg et al. (1978) and Ellis (1982) suggest that the movement sequence has to be loaded into a buffer first. Rosenbaum et al. (1984) suggest that a hierarchical tree has to be set up. Whatever the preparation mechanism is, it takes time. Hence, if a subject can prepare a sequence prior to a 'go signal', movement latency (i.e., simple reaction time) will be much smaller. However, more interesting is that both mechanisms imply specific processes during movement execution, namely retrieving movement information from a buffer, or traversing a hierarchical tree, respectively. Therefore, one may expect that the structure of the units in the writing pattern may affect movement duration. A known but unexplained effect is the observation that sequences of identical units take more time to execute than sequences of different ones. In our investigation, pairs of identical allographs show longer movement times than pairs consisting of different allographs, no matter whether their strokes are congruent or noncongruent. These data provide additional evidence for the hypothesis that allographs form the units that are retrieved from motor memory.

The observed stroke-duration effects are not only present in the simple-reaction time condition, where movement preparation can evidently take place, but also in all choice-reaction time conditions. This finding provides evidence that the process of preparation takes place even in conditions where movements have to be executed immediately. This conclusion is supported by Stelmach and Teulings (1983) who showed that execution characteristics in prepared and non-prepared handwriting patterns were very similar. Apparently, the process of memory retrieval also includes the preparation, or the setting up, of the movement sequence.

3. Motor Adjustment

The information retrieved from motor memory and used in the motor program of a certain writing pattern contains only the most invariant and essential information to control the muscles (See Chapter 2). The movement information not stored in motor memory still needs to be 'substituted' in the abstract motor program. This is done at the motor-adjustment level. The general idea is that the latter type of information may be different for each replication of a handwriting pattern. For example, while writing a line from left to right, the orientation of the hand changes. However, the effectors that are involved, seem to adjust themselves to varying arm orientations, so that the writing product's orientation and slant vary only marginally with hand orientation (Maarse et al., 1986). Therefore, it would not be efficient if orientation or slant parameters were stored with the allographs' movement information.

Many 'adjustable' parameters will no doubt exist, because the memory information is supposed to be parsimonious. These can be divided into *muscle-specific* and *non-muscle-specific* parameters. Van Galen and Teulings (1983), using an experimental paradigm based on Sternberg's (1969) additive-factor method, concluded that two separate levels are responsible for the substitution of these parameters: *parameter setting* and *motor initiation.* Van Galen and Teulings argued that the *size of writing* is not necessarily a muscle-specific parameter because writing size can be adjusted, within certain limits, without changing the roles of the muscles involved. However, *orientation* and *slant* are typically muscle-specific parameters. To argue this, the authors hypothesized that writing movements might internally be organized in terms of two axes of movement, one corresponding to finger-joint movements and one to wrist-joint movements. Therefore, changing orientation or slant would imply that the roles of these axes and the corresponding muscle systems change. This mechanism evoked our interest. The ease with which subjects change the orientation and slant of their writing, either voluntarily or induced by distorted feedback (Pick & Teulings, 1983), seems to deny that the hypothesized pair of axes, having a biomechanical basis, would correspond to the internal organization of movements.

In Chapter 4 the properties of wrist-joint and finger-joint movements are investigated. In the framework of this experiment the handwriting apparatus was modelled in terms of a system with actually three degrees of freedom. Namely, the wrist joint has only one degree of freedom, because during cursive handwriting the pen remains on paper. The system of finger joints possesses actually two degrees of freedom during handwriting, because they enable (small) pen movements in the two-dimensional plane. In order to investigate whether the wrist-joint and the finger-joint movements represent different effector systems (or main axes) with different properties, the subjects were asked to perform back-and-forth movements in all directions, and lines of normal cursive handwriting. The subject's forearm was immobilized because we wanted to record movements with a known forearm position. It appeared that the rate of stroke production was highest in wrist-joint movements whereas the average finger-joint movements were about 30% slower. Movements in intermediate directions were intermediately fast. Therefore, the rate of stroke production could be understood from the properties of the individual axes.

In order to obtain more certainty that these main axes correspond to two different subsystems the accuracy of producing straight lines was estimated. Wrist-joint movements of small amplitude appear to have the highest accuracy. This is not surprising in view of the fact that, in handwriting, they possess only one degree of freedom. Pure finger-joint movements in preferred directions were somewhat less accurate, which is also reasonable because here two degrees of freedom are involved. In accordance with the expectations, movements in intermediate directions, having three degrees of freedom, were least accurate.

Encouraged by the consistent data on stroke duration and stroke accuracy as a function of direction we investigated whether these movement axes correspond to the internally represented two-dimensional space. As wrist-joint and finger-joint movements show such large differences, it was suggested that these axes might be controlled independently at some internal level. This might contribute to slightly different time lags (e.g., Wadman et al., 1980, Kaminski & Gentile, 1986) or force-time curves (e.g., Meyer et al., 1982). Such differences would be very likely to occur in biomechanical systems that are so discrepant. However, no systematic differences could be found between the axes, which suggests that these axes have no substantial, independent internal representation as was supposed by Van Galen and Teulings. The lack of specialized axes in handwriting is consistent with our earlier findings that orientation and slant can be adjusted freely, and with our present findings that the subject's normal orientation and slant does not correspond to these main axes.

Chapter 2 concluded that the relative stroke durations are unlikely to be stored in motor memory. Consequently, relative stroke durations have to be substituted at the motor-adjustment level. This is efficient as relative durations depend upon various factors located at all levels of the motor system. A clear example is given by Gentner (1987), who found that increasing typewriting speed is not achieved by reducing all interstroke intervals proportionally. For instance, the double digraphs (involving repeated keying by the same finger) cannot be speeded up. Apparently, relative duration may depend upon the limitations of the muscle systems involved. Other examples illustrating this are the previously mentioned rate differences between wrist-joint movements and finger-joint movements. The general idea is that it must be assumed that the motor system is aware of the speed of its peripheral apparatus.

The previous discussion was concerned with typical muscle-specific parameters. Now we will discuss some non-muscle-specific parameters. An example of a non-muscle-specific parameter is writing size. It is generally assumed that overall size is not a parameter stored in handwriting patterns (E.g., see Chapter 2) and therefore has to be substituted at the motor-adjustment level. As these parameters will not be elaborated in this thesis, we will discuss the size parameter only briefly in relation to its effect on stroke duration. The duration of a stroke depends upon the context of surrounding stroke sizes. We distinguish three 'ranges' of context: macro, meso and micro context (Thomassen & Teulings, 1985). Macro context has a range of several writing patterns separated by a sufficient interval, e.g., involving a pen lift, to re-adjust all parameters completely. For small writing sizes, the required duration is more or less independent of writing size. However, for larger size, other muscles will be involved and size becomes a muscle-specific parameter. With increasing size, force levels approximate some (instruction-dependent) level, whereas duration increases proportionally. Meso context has a range of at least two strokes. If the relative sizes of two successive strokes in a writing pattern changes, both duration and force level are adjusted. Micro context has a range smaller than a single stroke. Here the time needed to perform a unit of length of handwriting trajectory depends on the local curvature, actually a quantification of shape. The more curved the trace, the slower the movement. The complex behavior of duration as a function of size and shape supports the notion that relative durations are not stored in motor memory.

4. Recording and Data Processing

Handwriting movements serve a specific purpose: the guidance of the writing instrument along the required spatial trajectory. Although the writing pen leaves a visible writing trace, this result is still too abstract for direct analysis in the present type of research. The concrete and measurable movement is the movement of the pen tip as recorded by means of a digitizer. Digitized data are entered into the signal-processing procedures and the various analysis techniques which are explained in Chapter 5. Obviously, recording of the pen tip exclusively implies a severe data reduction. Relating these recordings to three-dimensional recordings of wrist and fingers (e.g., Van Emmerik & Newell, 1988), or to EMG recordings (Vredenbregt & Koster, 1971) yields the rich information that might lead to understanding handwriting at the microscopic level.

In order to select the appropriate lowpass filtering characteristic, the spectral properties of the handwriting movements have been studied. An interesting result is that, from the signal-processing point of view, handwriting can be seen as a sequence of independent strokes. More important is the conclusion that the movements, considered as separate movement components in X and Y direction, can be simulated from the extremes of X and Y. This indicates that the movement information stored in the postulated motor memory is probably both parsimonious and complete.

Summary

The present series of experiments intends to elaborate a model of *handwriting-movement control* in terms of three *different levels of the motor system*: motor memory, memory retrieval, and motor adjustment. Finally, a signal-analysis level can be distinguished. *Motor memory* contains specific, parsimonious, static information about the handwriting movement (i.e., topological structure, relative stroke sizes, and stroking sequence). This information is used in the motor program that results in a writing pattern. Although handwriting patterns are executed as a continuous sequence of actions, the immense number of these lengthy patterns cannot be stored as such. Instead, a *memory retrieval* process is suggested which, prior to starting the writing pattern, retrieves the memory information as units, having the extent of a writing character. Finally, the information not stored in motor memory has to be substituted into the motor program at the next level by a highly complex procedure, called *motor adjustment.* One aspect elaborated here, is that of the properties of the wrist-joint and finger-joint movements. It appeared that these movements have different properties with respect to maximum rate of movement production. This may, for instance, form a reason why durations in fast handwriting are probably not stored. It appeared, furthermore, that the system allows the production of relatively accurate movements in the directions of each of the main axes, whereas movements consisting of a combination of these axes were less accurate. Finally, at the level of *signal analysis*, it has been shown that a motor memory containing the postulated information is probably adequately equipped to regenerate the recorded handwriting movements.

CHAPTER 2. LONG-TERM MOTOR MEMORY

This chapter intends to identify the 'primary' handwriting-movement information stored in long-term motor memory. We assume that this information is used in the motor program, generating a handwriting pattern. Schmidt et al. (1979) argue that "the motor program should be considered as an abstract memory structure containing codes capable of being transformed into *patterns* of movement. The patterns produced from a given program have certain invariant properties, even though two responses from the same program might have large differences in other aspects. Under this view, the program is *generalized*, so that *parameters* are required to specify the particular way in which the program is to be executed" (p. 417). Invariant properties in handwriting are well-known and have often been reported in the literature. For instance, Raibert (1977), cited by Schmidt (1982), demonstrated striking similarities between lines of handwriting, produced in different sizes or with different limbs. The reverse line of reasoning is that invariant properties in movement patterns might indicate that they originate from the movement information permanently stored in motor memory. However, this reversal is not necessarily true. Therefore, additional evidence is required from comparisons of various related invariant properties. Furthermore, patterns should be performed under several different conditions that allow execution of the same abstract motor program.

The different forms of movement information, which may be held responsible for invariant properties, can be divided roughly into spatial, temporal and kinetic forms of information. Spatial information contains, e.g., the topological structure of the allographs and the relative sizes of their strokes (which we will call *spatial characteristic*). In other words, the topological structure and the spatial characteristic describe the shapes of the allographs qualitatively and quantitatively, respectively. Temporal information contains, e.g., the stroking order and the relative stroke durations (to the latter of which we will refer as the *temporal characteristic*). Finally, kinetic information contains, e.g., the relative peak forces of the strokes (which we will call *force characteristic*) and the force-over-time curves per stroke.

We can argue that both the topological structure and the stroking sequence are part of the stored movement information. The topological structure, first of all, is responsible for the fact that a person's handwriting satisfies the requirement of legibility. Moreover, it also causes the within-writer variability to be much smaller than the between-writer variability (e.g., Maarse et al., 1988b). The stroking sequence is probably also part of the stored information. Indeed, a movement pattern executed with reversed stroking sequence, acts as a different motor program (e.g., Van Galen & Teulings, 1983; See also MacKay, 1982; Rosenbaum, 1977). This effect might be confounded with general preference rules in writing and drawing, which suggest a more fundamental origin of stroking sequences (Thomassen et al., 1988).

Force, Duration and Size

The major concern of the present chapter is to what extent the above-mentioned spatial, temporal, and force characteristics form the source information which the motor system uses to control movements. These characteristics are not fully independent such that the variance of one characteristic could be explained by the variance of another characteristic. For instance, Schmidt (1985) concludes that the high degree of invariance of the temporal characteristic in complex movement patterns seems to suggest that the temporal information is an essential part of the stored movement information. However, this temporal characteristic may still be of a 'secondary' nature, i.e., resulting from another, 'primary' characteristic. Therefore, a comparison among the invariances of interdependent characteristics will indicate the best candidate for 'primary' invariance.

The force characteristic has also been suggested as a fundamental information source. Schmidt et al. (1979) state that "At present, there has been the suggestion that the *phasing* of a response (i.e., the temporal relationships among various contractions within a movement pattern), as well as the *relative forces* in various contractions participating in the movement, may be fundamental invariant properties of motor programs." (p. 417, 418). According to their *impulse-variability model* on single-phasic aiming, back-and-forth aiming and rapid tapping tasks, both the variability of the force level and that of the movement duration, contribute to the variability of the movement distance. Meyer et al. (1982) provide mathematical improvements which they apply to achieve a description of two-phasic aiming movements (i.e., movements containing both an accelerative and a decelerative phase).

Their *symmetrical impulse-variability model* assumes that "the motor system has two distinct mechanisms for controlling an aimed limb movement: one associated with the force parameter f and one associated with the time parameter t " (p. 462). However, this model assumes duration rescalability (i.e., the proportional expansion or contraction of intervals), an assumption that may be questioned (Zelaznik et al., 1986). Although their model is apparently not perfect, it shows that different force-time curves can be derived, depending upon whether the correlations between the force and duration parameters are positive or negative. More interesting, in our view, is that the sign of the correlation tells us something about the causal relationship between size, duration and force parameters. This notion will be elaborated in the article which constitutes the kernel of the present chapter.

Graphonomics Contemporary Research in Handwriting
H S R. Kao, G P van Galen, R Hoosain (eds)

INVARIANTS IN HANDWRITING: THE INFORMATION CONTAINED IN A MOTOR PROGRAM

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INTRODUCTION

The notion of abstract motor programs for the performance of fast and complex motor patterns such as handwriting, is well established (e.g., Keele, 1981). Bernstein (1967), Klapp (1977), Lashley (1951), Morasso (1981), and Russell (1976) have argued that motor programs are unlikely to be represented in long-term motor memory in terms of concrete muscle contractions or joint flexions. But what type of movement information is in fact represented? It could be primarily spatial information as the latter authors suggest, or temporal information (e.g., Denier van der Gon and Thuring, 1965; Viviani and Terzuolo, 1982, Wing, 1978). This paper presents a method for searching for more and more invariant movement characteristics and it applies this method to the spatial and temporal characteristics of a handwriting pattern. The search for invariants is of interest because the most invariant movement characteristic under differing execution conditions should be closely related to the movement information stored in long-term motor memory.

According to the literature on motor programs, temporal as well as spatial characteristics have been claimed to be strikingly invariant, but the degrees of their invariance have never been compared. It has been shown, for example, that movement patterns performed by the same subject at different size and speed, or with different limbs (involving varying sets of muscles) show highly invariant spatial (Lyons, 1964; Merton, 1972; Smyth & Wing, 1984, Stockholm, 1979) and temporal characteristics (Cutting & Kozlowski, 1977; Denier van der Gon & Thuring, 1965; Katz, 1951; Keele & Summers, 1976; Shapiro, Zernicke, Gregor, & Diestel, 1981; Tuller, Kelso, & Harris, 1982; Viviani & Terzuolo, 1980; Wing, 1978).

Comparing Movement Characteristics

In order to compare the degrees of invariance of spatial and temporal characteristics, one has to derive an equation that relates both characteristics.

Equation of Movement Yields Four Characteristics

Handwriting movements can be adequately described in terms of the horizontal and the vertical coordinate of the pen position as a function of time An equation of movement (e.g., Bernstein, 1967, Wing, 1978) relates the exerted muscle force to the sum of the inertial (accelerative) forces and several friction forces along the horizontal and along the vertical axis The friction forces are small as compared to the accelerative forces and may therefore be neglected (Denier van der Gon and Thuring, 1965). The accelerative force may then be set proportional to the muscle force. Furthermore, we may restrict our study to the vertical component of the writing movements since this component appears to be the more sensitive one to variations in timing of the force bursts (Vredenbregt, Koster, & Kirchhof, 1969)

Starting from the simplified equation of movement (i.e., in the vertical direction and without friction forces) one can express the vertical size of a stroke in terms of stroke duration and peak force during the stroke (See Appendix A). But these data are not sufficient to provide a full description Also the shape of the force curve over time has an effect. The force-efficiency factor E expresses this effect: i.e., the stroke size produced while peak-force and stroke duration are given. In Appendix A it is shown that the vertical size (s) of a stroke is proportional to the square of the duration of a stroke (T**2), proportional to the peak force (which is in turn proportional to the peak acceleration A), and, finally, proportional to the force-efficiency factor of the force-time pattern (E):

$$s = E * A * T**2 \qquad (1)$$

Therefore, we shall define the following characteristics of a specimen of handwriting: the *spatial characteristic* (i.e., the sequence of vertical stroke sizes of a writing pattern), and the *temporal characteristic* (i.e., the squence of *squared* stroke durations). But if we wish to compare the spatial and temporal characteristics we should also consider the force-level and force-efficiency characteristics. Of course only three of these characteristics can be independent In principle, each of them could constitute the primary information in motor memory but the spatial and the temporal characteristics evidently seem to be the most promising ones. So we define the *force-level characteristic* by the sequence of peak accelerations of the strokes of a writing pattern and the *force-efficiency characteristic* by the sequence of force efficiencies. In fact, we are not interested in absolute measures (e.g., size, which is rather arbitrary), but in relative measures (e.g., the size ratios). Therefore the sequences have to be normalized first.

In order to compare the degree of invariance of these four characteristics we shall introduce three criteria The need for developing such criteria, which are to be based on the statistical relations between duration, distance travelled and applied force, has already been stressed by Wing (1978, p. 166).

Three Criteria to Identify the Most Invariant Characteristic

If the values of the four characteristics are indeed related as described by Equation 1, one can derive the following three criteria to decide whether the temporal, the spatial, or perhaps one of the other two characteristics (force level or force efficiency) are most invariant over replications of a specific handwriting pattern.

The first criterion employs the *signal-to-noise amplitude ratio* of a characteristic (as known in signal analysis, See Footnote 1) The 'signal' is the average characteristic while its 'noise' comprises the fluctuations between the average and a specific replication. Those movement characteristics that are primarily stored in a specific motor program should possess relatively little 'noise,' or a high signal-to-noise amplitude ratio

The second criterion employs *inter-characteristic correlation* coefficients. Let us suppose that the temporal characteristic constitutes the basic information from which the motor system computes the force and the force-efficiency characteristics (while the spatial one is simply following from straightforward mechanics). Longer-duration strokes and higher force levels normally go together (e g , Thomassen & Teulings, 1985). So we would expect that random fluctuations of the temporal characteristic (relative to the memory representation) are positively correlated with those of the force characteristic On the other hand, let us suppose that it is the spatial characteristic that constitutes the basic information from which the motor system computes the movement's further characteristics Following Equation 1 many combinations of values of the temporal, force, and force-efficiency characteristics, which all realize the intended spatial goal, could be chosen by the motor system If, for instance, the motor system happened to adjust the duration of a stroke greater than its average in that specific context, it could still obtain the intended stroke size by selecting a smaller force or force efficiency than their averages in that specific context. Under the latter condition correlations between temporal and force characteristics might become negative. Thus, one can discriminate between the two hypotheses by checking whether the correlation between the temporal and the force characteristics are significantly negative or positive.

The third criterion is concerned with the robustness of a characteristic (expressed by the *inter-condition correlation*) across various instructed global transformations of the movement pattern, such as writing at a different size or speed, or with respect to some arbitrary manipulation of the writing conditions such as writing without visual feedback, or writing on a low-friction surface while reducing proprioceptive feedback. We assume that the same centrally stored abstract motor program is in operation for each of these conditions (e.g., Stelmach & Teulings, 1983; Van Galen, 1980), whereas the less abstract parameters are adapted ad hoc during the writing because they pertain to the frequently varying writing circumstances. So the characteristic that shows the highest correlation across writing conditions within a subject is most likely to constitute the primary movement information in long-term motor memory.

EXPERIMENT

In this experiment the subjects repeatedly perform a specific writing pattern in a normal way as well as in three "unusual" conditions (writing larger, writing slower, and writing on a low-friction surface without visual feedback). These conditions are such that it may be expected that the same abstract motor program in long-term motor memory is involved. The recorded writing movements are subdivided into separate strokes and the normalized spatial, temporal, force, and force-efficiency characteristics introduced above, are calculated. Finally, each of the three criteria discussed (signal-to-noise ratio, inter-characteristic correlation, and inter-condition correlation) are applied in order to decide whether the spatial or the temporal characteristic is more invariant across replications and conditions.

Method

Subjects

Four male, naive right-handed subjects (psychology students and staff members, aged 23 to 31) participated in the experiment. They satisfied the requirement of producing the experimental writing pattern (*mehelmen*) cursively and without pen lifts. A fifth subject did not fulfill this requirement.

Materials

The positions of the pen tip during the writing movements were recorded by a computer-controlled digitizer (Vector General Data Tablet DT1) with an RMS error less than 0.2 mm. at a sampling rate of 200 Hz. A sheet of paper with a horizontal writing base line was attached onto the writing area. The subject wrote on another sheet of paper that covered the first one but the line was still visible. On every trial the top sheet was shifted upwards such that writing position and orientation could be maintained. In one condition the subjects wrote on a low-friction writing surface consisting of an overhead transparency sheet while the writing hand remained resting on a normal sheet of paper In this condition, moreover, the ball-point tip did not leave a trace behind, so that both proprioceptive and visual feedback were reduced.

Procedure

In order to initiate a trial the subject pressed the pen on the writing area and a buzzer sounded. The subject was instructed to keep the pen on the paper in a relaxed way until a second buzzer sounded after a random interval between 1000 and 3000 ms. in order to reduce the probability of artifacts due to anticipation. The subjects were instructed to wait for the second buzzer and then to write the pseudoword *mehelmen* cursively at a comfortable speed and without lifting the pen during the entire recording period of 4 s. The trace of the recorded movement was shown on a graphical display. If subject or experimenter were not satisfied the trial could be repeated, but once a trial had been accepted it was definitely adopted in the analysis. Each subject performed one series of 16 replications under each of the four different conditions. First they performed the *normal condition*. Then they performed a series under each of the following conditions in random order: write about twice as large as normal (*write-large condition*), write about twice as slow as normal (*write-slow condition*), and write normally on a low-friction surface (reducing proprioceptive feedback and visual feedback, *smooth-surface condition*). It should be mentioned that the recording period and sampling rate in the write-slow condition were adapted, they were 6 s and 125 Hz, respectively

Analysis

The writing pattern was divided into separate up and down strokes. Since for the present purpose we are interested in steady-state handwriting, the first four and the last five strokes were omitted. Therefore, the writing pattern *mehelmen* contains 29 − 9 = 20 target strokes. The strokes were identified automatically as follows. First, vertical velocity was determined from the sampled vertical position by differentiating and low-pass filtering (sinusoid transition band 8 to 24 Hz, see Teulings & Maarse, 1984) Time marks were calculated of those moments on which the vertical-velocity curve crossed the zero-velocity level (interpolating between samples). The height (or vertical size) of a stroke is the absolute difference in vertical position between two successive time marks. As defined in the introduction, the *spatial characteristic* is the normalized sequence of heights of the 20 successive strokes. The duration of a stroke is the interval between two successive time marks. The *temporal characteristic* is the normalized sequence of squared durations of the 20 successive strokes. The peak force of a stroke was estimated from the absolute maximum of the acceleration curve between two successive time marks. So the *force characteristic* is the normalized sequence of peak forces of the 20 strokes. The force efficiency per stroke can be determined from size, duration and peak-force values using Equation 1. The pattern of force efficiencies of the 20 strokes forms the *force-efficiency characteristic*

Results

Below, each of the three characteristics will give an answer as to whether the spatial or the temporal characteristic is the more invariant one.

The *signal-to-noise amplitude ratios* of each characteristic were averaged over subjects and conditions and yielded the following data: spatial 5.5; temporal 2.7; force 1.3; and force efficiency 0.9. So the spatial characteristic reaches the highest signal-to-noise ratio of all characteristics (sign test, N=16 subjects × conditions, x=0, p<.001). This is taken to support the hypothesis that the spatial characteristic, rather than the temporal characteristic, constitutes the more important information stored in the motor program. The force-efficiency characteristic apparently contains very little information so that it was decided to leave this characteristic out of our further comparisons.

The *inter-characteristic correlation* (between each pair out of the spatial, temporal and force characteristics) has been determined for each of the 20 strokes of the writing pattern. The correlations between the spatial and temporal characteristics and between the spatial and force characteristics are predominantly positive (sign test, N = 320 strokes × subjects × conditions, x=240 and 309, respectively, z>8., p<.001). However, more important is the significantly negative correlation between the temporal and force characteristics (sign test, N=320, x=52, z>12, p<.001). Apparently, duration fluctuations and force fluctuations are traded off against one another, governed by a higher-order control characteristic. This is again taken as evidence for the hypothesis that the spatial characteristic forms the primary information from which temporal and force characteristics are derived by the motor system.

On behalf of the *inter-condition correlation* (between the normal condition and each of the other three conditions) the average 20-stroke pattern of each characteristic has been calculated per condition and per subject. Correlations were determined between a characteristic's pattern under the normal condition and under each of the three other conditions. The inter-condition correlations of the spatial characteristic were on the average 0.99, those of the temporal characteristic were 0.95, and those of the force characteristic were 0.79. So the spatial characteristic reaches the highest correlations (sign test, N=11, x=1, p<.05). Apparently, of the three characteristics the spatial characteristic is the most robust one under execution variations that are arbitrary and supposedly irrelevant as to the retrieved motor program. This is again interpreted as supporting the hypothesis that the spatial characteristic is more likely to belong to the information primarily stored in the motor program than the temporal or the force characteristic.

Discussion

The present experiment demonstrated a method for determining whether the spatial or the temporal characteristic of a handwriting pattern is more invariant over replications under normal conditions as well as under voluntary transformations, or extraordinary execution conditions. The more invariant characteristic is assumed to be more closely related to the movement information stored in long-term motor memory. By means of an equation of movement we defined the spatial and the temporal characteristics and their relationship. The equation of movement required that two other characteristics should be considered as well: the force-level characteristic and the force-efficiency characteristic. At an early stage, however, the latter characteristic appeared to contain virtually no movement information. The degree of invariance of the other characteristics could be compared by means of three criteria. Applying these three criteria, we observed that the spatial characteristic showed the highest signal-to-noise ratio; that its component factors, viz., the temporal and the force characteristics, are negatively correlated; and that the spatial characteristic showed the highest inter-condition correlation. Since apparently the spatial characteristic is the more invariant one it is concluded that this characteristic is very closely related to the movement information stored in a handwriting motor program.

Disproof of Alternative Explanations

The negative correlation between time and force could have been introduced if the subjects would have inserted hard-to-detect pauses or hesitations during their writing, so that in one stroke the force level would decrease and the duration would increase. However, the present result is also found by Newell, Carlton and Carlton (1982) in single-phasic, ballistic arm movements were such hesitations are less likely.

The negative correlation between duration and force level cannot be explained either by a feedback mechanism which would adjust, in a quasi-simultaneous fashion, stroke duration such that the intended stroke size is realized (as might occur in slower drawing movements). This is unlikely, however, because we obtain similar results in the low-friction and reduced-feedback condition as in the normal condition.

One might suggest that the negative correlation between time and force is caused by the pen-paper friction (or the static friction; MacDonald, 1966) which inhibits the start of the actual pen movement and facilitates the stop while the pen attains a higher acceleration level. Since pen pressure appears to be modulated also very characteristically during writing (Kao, 1983; Lin, Herbst & Anthony, 1979; Tripp, Fluckiger, & Weinberg, 1957) this effect is probably even hard to isolate. However, evidence to rule out this explanation is again provided by the results under the low-friction condition because they were similar to the ones under the normal condition.

At first glance it is reasonable that the temporal characteristic is often argued to be part of the movement program. For instance, in gross arm movements it is duration that is adjusted to achieve a specific movement distance (Wadman, Denier van der Gon, Geuze, & Mol, 1979). However, Thomassen and Teulings (1985) argued that in gross movements, it is only duration that can be adjusted because force adjustment tends to level off In contrast, when small handwriting movements are generated, both duration and force level appear to be adjusted to approximately the same extent which, in fact, supports our notion of the higher-level control by the spatial characteristic.

Motor Learning

It is obvious that only those features that describe the desired outcome economically and conclusively, will be stored in a motor program. Handwriting is a typical graphic skill from the first time of writing instruction onwards and therefore the spatial characteristic defined and employed in the present paper is likely to be closely related to the more fundamental movement information stored in the handwriting motor program. On the other hand, in spatio-temporal skills where storing temporal information is essential (e g , tapping, dancing, conducting an orchestra) one would expect that the temporal characteristic is more invariant In the latter class of skills, it appears, moreover, that only timing patterns with simple interval ratios can be stored in motor memory (Povel, 1981), whereas the timing patterns in handwriting do not show any tendency towards restrictions to such simple interval ratios A practical conclusion of the present research might be that in efficient writing instruction the pupil should be trained to generate mentally the spatial goal positions (Pantina, 1957) and to produce smooth strokes connecting these goals (Søvik, & Teulings, 1983)

Invariant Temporal Characteristics Induced by Lower-order Mechanisms

Although the temporal characteristic probably does not constitute the primary source of movement information in the motor program, it actually serves as the most convenient and forgery-proof procedure for signature verification algorithms (e.g , Crane & Ostrem, 1983, Lin, Herbst & Anthony, 1979). It cannot be denied that several spatial aspects appear to be highly discriminative between subjects (Maarse, Schomaker, & Teulings, 1985). One explanation for the fact that the temporal characteristic still displays such a high degree of invariance might be that the motor system is well-trained in producing the smoothest trace that satisfies the desired spatial outcome. A smooth trace will contain in general various curvatures in clockwise or counterclockwise direction If we suppose that in a system of two independent antagonistic muscle groups the refractory period of a muscle group is about 200 ms., one can argue that the time needed to describe one circle is also at least 200 ms. In general, the amount of time needed to describe a part of a circle is more or less proportional to its arc length (in degrees) which implies an approximately constant ratio between velocity and curve radius (Viviani & Terzuolo, 1980; Hollerbach, 1981) or at least may show some definite relation between velocity and radius (Laquaniti, Terzuolo, & Viviani, 1983, Thomassen & Teulings, 1985). Because of the invariant spatial structure, the temporal characteristic in handwriting movements will in practice be highly invariant also, but it can never be more invariant than the spatial characteristic because it is derived from it.

Even in timed tapping tasks one might doubt whether the task is stored in terms of a temporal characteristic. For example, Keele and Summers (1976) trained two groups of subjects to reproduce various keying sequences according to two different interval patterns (either repetitively 500-100-100 ms or 500-500-100 ms.) but they noted that during the actual reproduction the ratio between the long and the short interval was not 5 to 1 but rather 2 to 1, which could be evidence of the storage limitations of a timing sequence (cf, Povel, 1981). However, during the next session the subjects were told to reproduce the keying sequence as rapidly as possible while timing structure was no longer important They found that some time structure was retained and concluded that timing is an integral part of the motor program. They restricted their conclusion, however, by noting that this is apparently true only for certain interval patterns, while for other patterns the trained time structure deteriorates rapidly, e.g., for those patterns without a simple four-beat interval pattern. Close inspection of the final-session interval data shows, however, that the temporal structure of each deteriorated pattern tends to become identical. In fact, this is in favour of the interpretation that the retained temporal structure is not primarily stored in a motor program, but merely the consequence of the hierarchical structure of the movement pattern induced by the periodicity of the interval pattern

The above examples intend to demonstrate that various lower-order mechanisms may bring about systematic timing properties without providing evidence, however, that a temporal characteristic is itself stored in the abstract motor program of a handwriting pattern.

FOOTNOTES

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1. The signal-to-noise amplitude ratio (i.e., the square root of the signal-to-noise energy ratio) can be estimated as follows: First we calculate the variance of the mean *varxmean* (i.e., the variance across the 20 strokes of the means over replications) and the mean variance *varx* (i.e., the mean over strokes of the variances across the 16 replications). The signal-to-noise amplitude ratio is defined as the square root of the quotient of the variances of the signal (which is estimated by varxmean

* n/(n−1) − varx/(n−1)) and of the noise (which is estimated by (varx − varxmean) * n/(n−1)) where *n* is the number of replications.

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APPENDIX A

Equation of Movement

The net vertical distance (s), travelled by the pen tip during a stroke, i.e., between two moments of time at which the vertical velocity is zero (Say at $t = 0$ and $t = T$, respectively), can be expressed in terms of the acceleration as a function of time ($a(t)$) as follows.

s = Integral[0,T]dt' [Integral[0,t']dt a(t)] (A1)

The acceleration curve a(t) can be rewritten in terms of amplitude A, duration T, and time function a' having amplitude 1 and duration 1, as follows:

a(t) = a'(t/T) * A (A2)

Substituting Equation A2 into Equation A1 yields the equation that plays a central role in this paper:

s = E * A * T**2 (A3)

where factor E is a so-called force-efficiency factor:

E = [Integral[0,1]dr' [Integral[0,r']dr a'(r)] (A4)

which contains information only on the shape of the acceleration curve during a stroke and which expresses how efficiently force bursts having a specific peak force and total duration are converted into a vertical displacement s.

Discussion

Generalization to Other Writing Patterns

The result of our investigation is that the spatial characteristic (i.e., the sequence of relative sizes between the strokes) is most invariant. Therefore it is probably part of the 'primary' movement information stored in a motor program. In fact only the vertical size component has been studied, disregarding its relation with the horizontal size component. Some aspects related to the coordination of both components will be discussed in Chapters 4 and 5. The present result was obtained by investigating only one writing pattern, consisting of a specific sequence of allographs. In order to generalize the results to other writing patterns, it is sufficient to discuss what the data would be for a permutation of the sequence. The answer may be extrapolated from the data in Thomassen and Schomaker (1986). They investigated the cursive writing of all possible four-letter sequences composed of the letters *e* and *l*. Their data indicate that context effects in terms of stroke *sizes* are small compared to the size difference between *e* and *l*. This implies that the spatial characteristic of the permutated sequence can be predicted on the basis of just the individual allographs. However, context effects in terms of stroke *durations* seem to be of about the same magnitude as the duration difference between *e* and *l*. This can be understood easily: a long sequence of *e*s is written in approximately the same speed as a long sequence of *l*s. However, when approaching the transition from one size to the other (e.g., from *e* to *l*), timing of the preceding letter appears to anticipate that of the subsequent letter. This implies that the temporal characteristic of the permutated sequence cannot be predicted accurately on the basis of just the individual allographs. Therefore, these data provide further evidence that temporal information is unlikely to be part of the 'primary' movement information stored in a motor program.

Rescalability of Size and Duration

In our investigation, rescalability of size and duration was assumed when estimating the signal-to-noise ratios and when comparing the size and duration transformations. However, this assumption deserves a little more attention. Rescalability has to be considered for two types of variation of the writing pattern: unintentional, random variations and intentional, overall variations.

1. Unintentional Variations

Let us first consider *size* rescalability in unintentional writing variations. In our experiment, the handwriting patterns were performed under maximally constant conditions. However, the individual reproductions of a pattern always differ slightly. This difference can be described by a systematic overall size parameter, plus 'random' variations of each individual stroke. An unpublished analysis of our data showed an overall size parameter for each subject and condition (Kendall's coefficient of concordance, $N = 20$, $k = 16$, $0.65 < W < 0.93$, $p < 0.01$). A significant overall size parameter has also been found in zig-zag patterns: the stroke sizes of all pairs in the zig-zag patterns, tend to be positively correlated (Stelmach & Teulings, 1987). Although it is uncertain whether the size variations are proportional, these data indicate that it is necessary to rescale, or normalize, the stroke sizes per pattern in order to obtain an unbiased signal-to-noise ratio.

Let us now consider *duration* rescalability in unintentional variations. Again, the stroke durations in replicated writing patterns may differ in terms of an overall duration parameter, plus individual stroke variations. However, Stelmach and Teulings (1987), studying the production of zig-zag patterns, found no support for any overall duration parameter: durations of nonadjacent pairs of strokes were not significantly correlated. In typing, an overall duration parameter seems to exist but, in general, it is not of a proportional nature (Gentner, 1987). In handwriting studies, however, the results are not consistent. Viviani and Terzuolo's (1980) data support the proportional nature but Hollerbach's (1981) data do not. Whatever the theory of duration rescalability is, a powerful analysis of the data collected in the present experiment show the presence of an overall duration parameter for each subject and condition (Kendall's coefficient of concordance, $N = 20$, $k = 16$, $0.11 < W < 0.69$, $p < 0.01$). Although the concordance here is one order of magnitude smaller than that of the stroke-size data, this result indicates that an unbiased signal-to-noise ratio also requires the normalization of the stroke durations per pattern.

Various normalization procedures have been proposed in order to rule out overall variation as much as possible. The *homothetic transformation* (Viviani & Terzuolo, 1980) maximizes signal-to-noise ratio but requires considerable calculation. Almost as accurate, but much faster to calculate, is the *proportional transformation* (Gentner, 1982). We used a straightforward *normalization* of the overall size. We do not expect any big differences between these transformations, because the range of the variation is small and the number of strokes in a single pattern is large.

2. *Intentional Variations*

We shall now look into size rescalability in intentional overall variations. In our experiment, the subjects were instructed to write the same pattern in different overall size or duration. The underlying assumption was that overall size and duration are *parameters* of the motor program. This would imply that a simple (not necessarily proportional) transformation exists between the stroke sizes of patterns written in different overall sizes. A characteristic involving a 'simple' transformation is assumed to be more basic, or 'primary' than one involving a complex transformation. This criterion is still quite liberal as compared to Gentner's (1982, 1987) proportionality requirement. As the transformation is not precisely known, a linear transformation is taken as a first-order approximation. Hence the inter-condition correlation can be used as a criterion for the quantization of the 'simplicity' of the size and duration transformations.

What do our data reveal about the intentional *size* variation? The high correlations between the stroke sizes of differently-sized writing patterns (in the order of 0.99) suggest that the linear approximation is extremely accurate. However, the picture is possibly slightly flattered because vertical stroke length in handwriting is roughly quantized into two levels. No conclusions can be drawn about proportionality, or rescalability, of size.

Let us now discuss the linearity and the proportionality of intentional *duration* variation. Since recent studies have analyzed movements more and more in detail (e.g., Zelaznik et al., 1986; Gentner, 1987), the proportional transformation of duration in intentional overall variations does not seem to be acceptable any longer. In the case of typing, Gentner indicates why: speed instruction affects mainly two-hand digraphs, but not same-finger doubles. The latter cannot be speeded up beyond a certain limit due to peripheral constraints. The lower degree of duration rescalability in comparison to size rescalability is probably the reason why our inter-condition correlation yields a somewhat smaller value for duration data than for size data (0.95 versus 0.99). As will be clear from Gentner's analysis, the difference might have been even bigger if conditions of speeded-up handwriting would have been included. All these considerations support the conclusion that the temporal characteristic is probably not stored in motor memory and that the spatial characteristic is the best candidate for the 'primary' movement information.

CHAPTER 3. MEMORY RETRIEVAL

The preceding chapter dealt with the nature of information most likely to be stored in the long-term graphic motor memory. The conclusion was that the handwriting movement information probably consists of the allographs' topological structure, stroking sequence and spatial characteristic (i.e., the size ratios of successive strokes). The present chapter intends to estimate the extent of the information packages which are retrieved from the long-term motor memory as units. These memory units are probably not as large as complete words (except for brief, highly practiced sequences such as most signatures). The latter would require a huge memory capacity proportional to word length times the number of different words. Therefore, the extent of a memory unit will be, at most, one or several allographs.

The smallest movement entity to be considered as a realistic candidate for a unit, is the stroke. A stroke is the movement between two successive points of high curvature. In fast handwriting by skilled writers, these segmentation points can be conveniently found, by searching for relative minima of the absolute velocity as a function of time (Thomassen & Teulings, 1985). A stroke is a realistic unit because the strokes in a writing pattern can be regarded as relatively independent segments (See Chapter 5). Two classes of strokes can be distinguished: congruent strokes, strokes having the same turning direction (clock- vs anticlockwise) but differing in size or orientation (up- versus downward), and noncongruent strokes, which differ in addition in turning direction. Arguments exist that congruent strokes may be regarded as identical units. Namely, writing patterns of differing sizes lead to the same slowing-down effects as same-sized patterns (Wing et al., 1979; See also Chapter 2). Furthermore, according to Hollerbach's (1981) oscillation model, series of several up and down strokes of handwriting can be generated by a single set of movement parameters. Therefore, two different allographs, constructed of congruent strokes, could act as identical or as different allographs, depending upon whether strokes or allographs form units in motor memory. In order to discriminate between the hypotheses (1) that the movement units in motor memory are single strokes and (2) that these are whole allographs, an experiment is conducted, which is reported in the present chapter.

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PREPARATION OF PARTLY PRECUED HANDWRITING MOVEMENTS: THE SIZE OF MOVEMENT UNITS IN HANDWRITING *

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In the present study we investigated whether individual strokes or complete letters form "movement units" in cursive handwriting In various reaction time (RT) paradigms (choice-RT, precue-RT, and simple-RT) we tested which definition of a unit provides the best explanation for the reaction-time and movement-duration data that we observed In the choice-RT condition we found that congruence of complete letters facilitated reaction time, but congruence of strokes within letters did not. This was also found to hold in the precue conditions where, some time prior to the imperative stimulus, a precue was presented, specifying either the first or the second letter of the writing pattern. Furthermore, analysis of movement durations revealed that the strokes immediately preceding and following the connection stroke between two identical letters were delayed These results consistently point towards the notion that the movement pattern of a well-practised letter is handled as a single unit

Introduction

In complex motor tasks such as Morse coding, typewriting, speech and cursive handwriting, the performer produces a seemingly continuous stream of movements. Such a stream of movements can, however, be regarded as a discrete sequence of movement segments, or *units*. In speech, the movement units appear to be as large as groups of words, and in typing, as small as a single key stroke (Sternberg et al. 1978).

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Also in handwriting some evidence for the existence of units is given by Van Galen and Teulings (in prep.). In the present article, we pose the question whether in handwriting individual strokes, groups of strokes, complete writing letters, or even groups of letters form units of movement.

There are at least four paradigms available with the help of which one could in principle estimate the size of a movement unit. The first paradigm is derived from Klapp and Wyatt (1976), who found that in choice-RT conditions, sequences of two identical Morse-key responses (e.g. long-long) require on the average 109 msec shorter RTs than sequences of two non-identical responses (e.g. long-short). They suggested that RT is longer when two (different) responses (or units) must be retrieved from a long-term motor memory, than when just one unit must be retrieved, which they supposed to be the case with two equal responses.

A *second paradigm to produce evidence for some definition of a unit* of movement is precueing separate elements from the sequence of movement elements prior to the imperative stimulus. Originally, precueing techniques were employed to investigate the possibility of preparing separate dimensions of movement tasks independently (Rosenbaum 1980; Zelaznik et al. 1982). In the present experiment we precued the identity of either the first part or the second part of the writing patterns. From studies on repetition effects in drawing tasks we know that repetition of a motor pattern reduces the memory retrieval time (van Galen 1980). We expected to find such a reduction of the retrieval time also in the partly precued conditions, in which subjects are informed about some of the parts of the writing pattern prior to the imperative stimulus: the remaining part should then be retrieved faster if it contains the same units as the precued part.

A third paradigm is presented by Sternberg et al. (1978). In simple-RT conditions the response can be highly preprogrammed, even to the extent that effects of certain task variables (e.g. a long versus a short Morse-key response) on RT disappear, provided that the subject has received enough practice (e.g. 100 trials; Klapp et al. 1974). However, according to Sternberg et al. (1978), simple RT is still affected by the number of movement units contained in the prepared motor task and does not show any tendency to disappear with practice. They found an RT increase of about 10 msec per unit in a speech sequence (a unit being one stress group), or in a typing sequence (a unit being one key stroke), irrespective of the size of the unit (e.g. of the number of syllables within one stress group).

A fourth paradigm, which may be employed to identify units in handwriting is based upon movement-duration data. Apart from demonstrating similar increases of the duration per unit as a function of the number of units in the sequence or as a function of serial position, Sternberg et al. (1978) also showed that sequences of identical units were executed at a significantly lower rate (e.g. to pronounce two identical words takes on the average 27 msec longer than to pronounce two different words).

The present study attempts to answer the question as to what is the size of a unit by investigating which of two different definitions of a unit (one stroke vs. one letter) is most compatible with the observed effects of the structure of the writing pattern upon movement-preparation time and movement duration. Subjects wrote a pair of cursive letters in choice-RT, partly precued-RT, and in simple-RT conditions. The letters consisted of either clockwise or counterclockwise turning strokes. The letter pairs contained either repetitions or alternations of identical units, defined in terms of letters and/or in terms of strokes. Repetition of letter identity was the case if both letters of a pair were identical. Repetition of strokes was the case if the turning direction of one of the letters was the same as the turning direction of the other one. If complete letters form the units, pairs of identical letters should be initiated faster both in choice and in precue conditions. On the other hand, if single strokes form the units, letter pairs consisting of similar strokes should also be initiated faster. Furthermore, in the simple-RT condition, sequences of identical units should be executed at a lower rate than sequences of different units and RT should vary only with the number of units in the sequence. Again, which definition is best supported will depend upon whether an increase of movement duration is found only in identical letter pairs or also in pairs with similar strokes.

Experiment

We studied movement-preparation time (RT) and movement duration of individual up and down strokes of handwriting patterns, consisting of all possible pairs of the letters *e*, *u*, *j*, and *n* (see fig. 1). The cursive letters *e* and *u* consist of counterclockwise turning strokes, and the letters *j* and *n* consist of clockwise turning strokes. Thus, we have three levels of *Letter Congruence* identical pairs (e g *ee*), similar pairs (i e both letters consist of strokes with the same turning direction, e g *eu*) and, nonsimilar pairs (i e all other pairs of letters, e g *ej*)

There were four *Stimulus Uncertainty* conditions one in which, prior to the imperative stimulus, the *S* received full advance information on both letters (simple condition), two partial precue conditions in which the *S* received advance information on the first (precue first) or the second (precue second) letter, and a full choice-RT condition in which the *S* received no advance information (choice condition) The experiment's specific purpose was to test whether the predicted effects upon RT and upon movement duration per stroke occur between identical and similar pairs or between similar and nonsimilar pairs

Method

Subjects

*S*s were 17 right-handed psychology students who had no difficulties with cursive handwriting During the analysis it appeared that four *S*s showed too many errors in their responses, (i e in more than 9% of the trials, whereas the average error rate of the accepted *S*s was 5%) so that only 13 *S*s were included in the analysis, 6 males and 7 females, aged 18 to 31

Apparatus

The writing movements were recorded by a computer controlled digitizer (Vector General Data Tablet DT1) The position of the tip of the electronic pen, expressed in its horizontal and vertical coordinates with a combined RMS error better than 0 2 mm, was sampled at a rate of 200 Hz The pen tip was an ordinary ballpoint refill The *S* wrote on an ordinary sheet of paper The digitizer was positioned such that the *S*'s individual writing slope was parallel to the horizontal axis of the digitizer Direct vision of the writing hand was eliminated by a piece of board

A display (Vector General Graphics Display Series 3 Model 2DS with P4 phosphor) was positioned at a distance of 125 cm right in front of the *S* at eye level The display allowed the tachistoscopic presentation of stimuli The stimuli were built up within 1 msec

Writing patterns

A handwriting trial consisted in the cursive writing of a pair of the letters *e*, *u*, *j*, *n* which had to be written without pen lifts (see fig 1), at maximum speed and in a comfortable size The *S* was not allowed to omit one of the up or down strokes at the start or at the end of the trial Preceding and following each trial, the pen had to remain resting on the paper The dot on the *j* had to be omitted

We define a stroke as a segment bounded by time moments at which the vertical component of the velocity changes sign (see fig 3) Letters *e* and *j* thus consist of 3 strokes and letters *u* and *n* of 5 strokes The letters *e* and *u* are built up of counterclockwise strokes The letters *j* and *n* are built up of clockwise strokes

The writing pattern could be one of the four identical pairs (e g *ee*), one of the four similar pairs (i e when both letters consist of strokes with the same turning direction e g *eu*), or of one of the eight nonsimilar pairs (i e when the letters have strokes with different turning directions e g *ej* and *en*) We thus have three levels of Letter Congruence

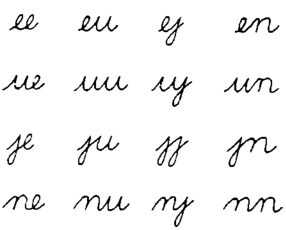

Fig 1 The writing patterns used in the experiment They consisted of all pairs of the cursive letters *e u*, *j* (without a dot) and *n*

Procedure

Each trial had to be performed as fast as possible when the imperative stimulus was flashed on the display screen The *S* had to write without visual feedback from the writing hand in order to prevent possible extra delays due to head and eye movements Prior to the imperative stimulus the *S* was presented a precue containing zero, one, or two of the letters There were four types of precue both letters (simple condition), only the first letter (precue first condition), only the second letter (precue second condition), or no letter at all (choice condition) We thus have four levels of Stimulus Uncertainty Precue and imperative stimulus were presented on the display screen in cursive handwriting If a letter in a given position was not precued, an asterisk appeared in its place (see fig 2) The precue and the imperative stimulus were scaled in sizes, such that they fit within a square of 9 cm × 9 cm in the centre of the display screen Additionally, the precue was enclosed in a square of 27 cm × 27 cm in order to make it clearly distinct from the imperative stimulus

A trial consisted of the following phases (see fig 2) First the precue was presented for 750 msec During the following 660 msec the screen was dark Then, for 90 msec, the imperative stimulus flashed on During the subsequent 2000 msec the writing movements were recorded After another 1000 msec the recorded writing movement was displayed (fitted again within a square of 9 cm × 9 cm) on the screen for 1500 msec, together with the reaction time, defined as the latency between stimulus onset and movement initiation We motivated the *S* to use the precued information in order to obtain short reaction times Following erasure of the screen there was a 1000 msec pause before the next trial started

Each Stimulus Uncertainty condition was run in a separate series consisting of 88 trials Each of the 16 patterns was replicated five times and in addition eight catch trials were inserted In catch trials the precue appeared undistinguishable from non-catch trials, but instead of the imperative stimulus two asterisks were presented, informing the *S* to hold the pen in its starting position (The number of erroneous starts in catch

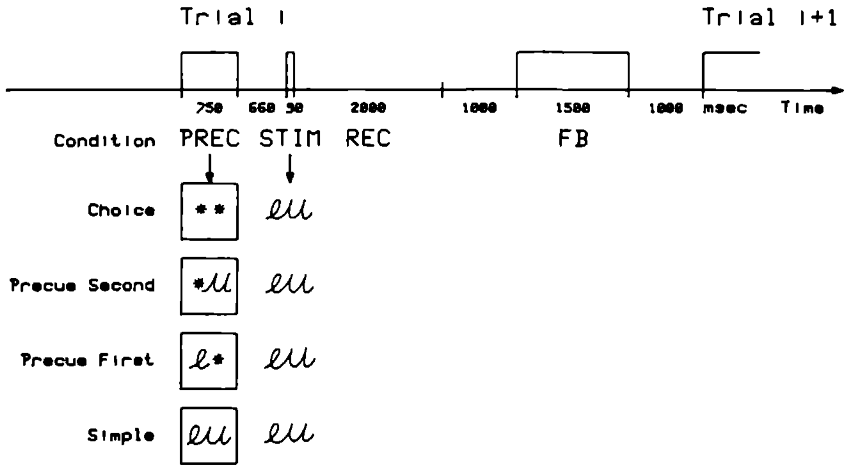

Fig. 2. Representation of the temporal structure of a trial. The numbers on the time axis specify the durations in msec of the following phases. precue (PREC), foreperiod, stimulus (STIM), recording of the writing movement (REC), delay, feedback of response and reaction time (FB), pause before the next trial starts, respectively. Boxes specify the phases during which the screen displayed information For the writing pattern *eu*, as an example, precue and imperative stimulus are given for each Stimulus Uncertainty condition

trials is estimated to be less than 10% in the simple and precue first conditions and 0% in the precue second and choice conditions.) Each series had a different random order without any restrictions. The order of the four Stimulus Uncertainty conditions was counterbalanced over *S*s. Before the *S*s performed these four experimental series, they were trained in each Stimulus Uncertainty condition according to the order simple, precue first, precue second, and choice, respectively. Each of the training series consisted of 18 trials, two of which were catch trials.

Analysis

The recorded writing movements (i.e. the horizontal and vertical coordinates as a function of time) were differentiated and low-pass filtered at 16 Hz (transition band 8 to 24 Hz) yielding their velocity (cf. Teulings and Thomassen 1979). Time marks were determined at which the vertical component of the velocity changed sign (see fig. 3). Hence, intervals between these time marks equaled the durations of the individual up and down strokes. Reaction time is defined by the interval between the onset of the stimulus and the onset of the first stroke.

In order to eliminate the effects of outliers in separate replications, only medians over the five replications of each of the 16 patterns within one series were entered in the statistical analyses (cf. Noordman-Vonk and Noordman 1979). The connection stroke, i.e. the final stroke of the first letter of the initial stroke of the second letter, cannot be compared within the 16 patterns. Therefore first and last stroke of each letter were

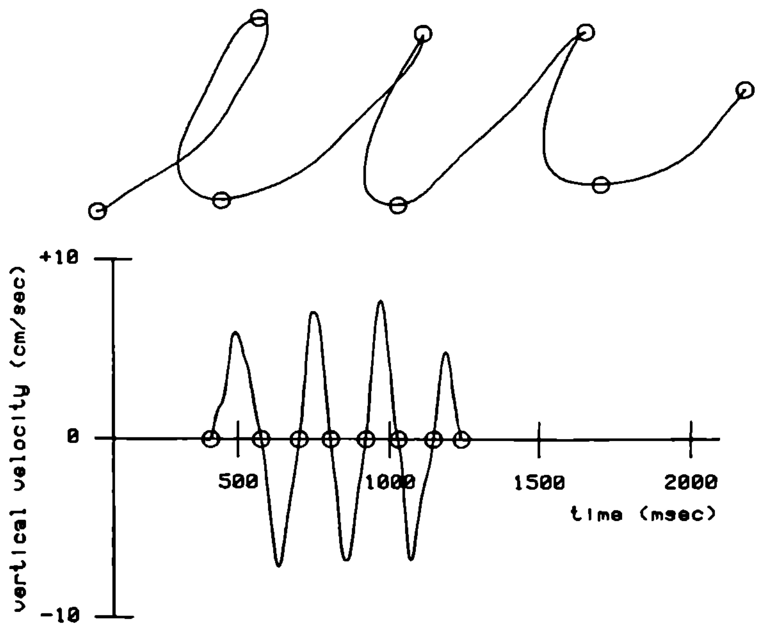

Fig 3 An example of the analysis of a trial Above the filtered writing trace is presented Below the vertical component of the velocity as a function of time is shown together with the time marks detected by an algorithm The corresponding time marks are also plotted in the writing trace

excluded from further analysis So, besides reaction time (RT), we studied the movement durations of stroke 2 and, for *u* and *n* only, stroke 3 and 4 of the first letter and, analogously, of the second letter

Results

Reaction time

The differential effects of Stimulus Uncertainty (simple vs precue first vs precue second vs choice) and Letter Congruence (identical vs similar vs nonsimilar) of the handwriting patterns were tested by means of a Subject × Stimulus Uncertainty × Letter Congruence analysis of variance with number of levels 13, 4, and 3, respectively We found a significant interaction between Stimulus Uncertainty and Letter Congruence ($F(6,72) = 2\ 3$, $p < 0\ 05$) (see fig 4) Apparently, RT is reduced in patterns of identical letters as compared with the collection of similar and of nonsimilar letter pairs in choice and in precue second condition (sign test, $N = 26$, $x = 7$, $p < 0\ 05$, one-tailed) and less clearly in the precue first condition There appears to be no interaction between Letter Congruence and Stimulus Uncertainty, if the level of the simple condition is left out ($F(4, 48) = 0\ 82$, $p > 0\ 05$) The RT increase which occurs between

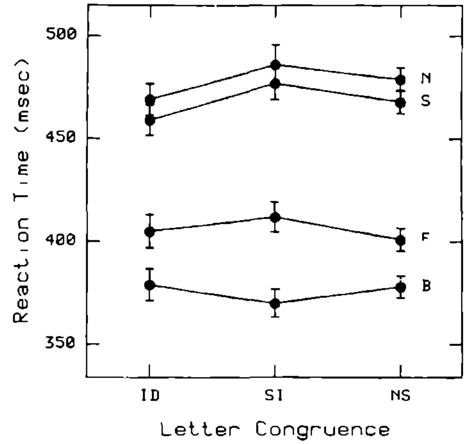

Fig. 4 Reaction times in msec for writing patterns of the three Letter Congruence levels: identical pairs (ID), pairs consisting of strokes with similar turning directions (SI) and with nonsimilar turning directions (NS) The reaction times are presented separately for each of the Stimulus Uncertainty conditions: simple (B), precue first letter (F), precue second letter (S), and full choice (N). Vertical bars at each data point represent reliability intervals of plus and minus one standard deviation of the mean, based on between-subjects variability.

identical and similar patterns and not between similar and nonsimilar patterns, provides strong evidence that complete letters rather than individual strokes form units. The behavior of the simple condition is quite different: There are no similar effects on RT.

There is a strong Stimulus Uncertainty effect ($F(3, 36) = 32$, $p < 0.001$): mean RTs in simple, precue first, precue second and choice conditions were 376, 405, 468 and 478 msec, respectively. The 10-msec difference between precue second and choice condition reached $p < 0.06$ (Newman-Keuls). From these data we may conclude that although the direction of the initial stroke was about the same in all tasks the *S*s did not employ the strategy to perform the very first up-stroke before they had programmed at least one letter.

In order to check whether letter frequency differences could be responsible for these results we performed a Subjects × Stimulus Uncertainty × Letter-1 × Letter-2 analysis of variance with number of levels 13, 4, 4, and 4, respectively. We found a main effect of Letter 1 ($F(3, 36) = 3.7$, $p < 0.05$) but none of Letter 2 ($F(3, 36) = 1.2$, $p > 0.05$). Patterns starting with *n*, *j*, *e*, *u* had RTs of 423, 429, 433, 442 msec, respectively. The Letter-1 effect does not appear to be correlated with letter frequencies in Dutch (cf. Rolf 1980) even if we take letter position (first one or two letters of a word) and bigram frequency into account. This lack of correlation may be seen as a confirmation of our implicit expectation that, although we used normal writing letters, no lexical effects on RT are present in two-letter sequences (cf. Hulstijn and Van Galen 1983). The absence of any Precue × Letter-1 interaction ($F(9, 108) = 1.37$, $p > 0.05$) shows that the effect is equally present in simple, precue and choice conditions.

The number of strokes in the writing pattern did not appear to have any systematic RT effect, either in the simple-RT condition or in any of the choice conditions To check this, we rearranged the 16 patterns into two groups of 5 versus 7 strokes in total, with Letter 1 balanced, and analogously into two other groups of 7 versus 9 strokes In the two additional Subjects × Stimulus Uncertainty × Number of Strokes analyses of variance neither Number of Strokes nor its interaction with Stimulus Uncertainty appeared to be significant ($p > 0\,05$) If it holds that the effect of the number of units has not yet reached its ceiling at 9 units (the total performance duration of 9 units is about 1100 msec), this finding provides some support for the notion that individual strokes probably do not form the unit

Movement duration per stroke

In order to test whether movement durations in sequences of identical units were increased, a Subject × Stimulus Uncertainty × Letter Similarity analysis of variance was performed for each stroke separately We focused upon the Letter-1 × Letter-2 interaction The probability of this interaction for the third, second and first stroke preceding the connection stroke was $p = 0\,7$, $0\,08$, and $0\,08$, respectively, and for the first, second and third stroke following the connection stroke, it was $p = 0\,01$, $0\,03$, and $0\,1$, respectively Inspection of the movement durations revealed that mainly the two strokes following the connection stroke took more time if first and second letter were

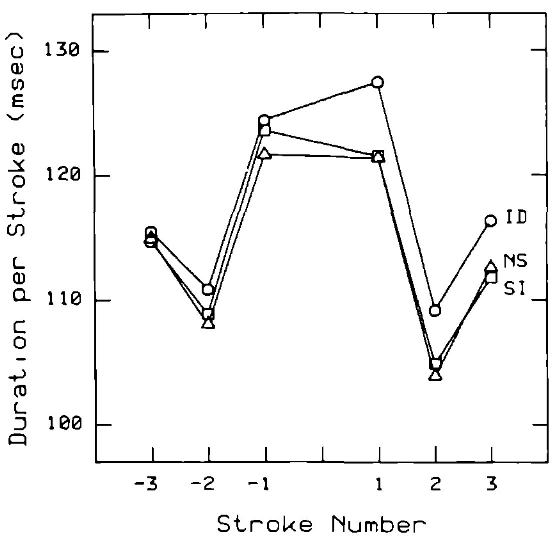

Fig 5 Movement durations in msec of the third, second, and first stroke before the connection stroke and of the first, second and third stroke after the connection stroke for each of the three Letter Congruence levels identical pairs (ID), pairs consisting of strokes with similar turning directions (SI) and with nonsimilar turning directions (NS) (averaged over all Stimulus Uncertainty conditions)

identical (sign test, $N = 26$, $x < 8$, $p < 0.05$, one-tailed) (see fig 5) The average delay in identical letter pairs relative to the other patterns for each of the three strokes preceding the connection stroke was 0.7, 2.5, and 2.1 msec, respectively, and for each of the three strokes following the connection stroke, it was 6 0, 5.0, and 4.2 msec, respectively. Leaving the indefinite effects of the connection stroke out of consideration, we find that identical letter pairs as a whole take about 20 msec more time Since there is no such effect between similar and nonsimilar patterns, this finding once more provides evidence that complete letters, rather than single strokes, form the units of movement

Note that the above interactions were based on the averages over all levels of Stimulus Uncertainty, since this factor did not have any systematic effect upon movement duration per stroke except for two out of the 24 interactions (which yielded $0.01 < p < 0.05$), all effects with factor Stimulus Uncertainty were non-significant at the 0 05 level

Discussion

The results of the present experiment consistently suggest that complete letters can be regarded as the units of movement in handwriting. This has been concluded from the finding that the expected effects on reaction time and movement duration occurred between identical and similar letter pairs. If the unit would have been the single stroke, then the expected effects would also have appeared between similar and nonsimilar letter pairs.

There are still a number of problems inherent in the experimental procedure. One might object that the varying number of alternatives of the imperative stimulus due to the precue makes the various Stimulus Uncertainty conditions incomparable (Zelaznik 1978). However, the number of response alternatives is assumed to have an additive effect upon all Letter Congruence levels within the same Stimulus Uncertainty level since it is supposed to work on the response choice stage only (Sanders 1980). The size of the reduction will, moreover, be minimal if stimulus and response are highly compatible (Smith 1977), as in the present experiment.

One might suppose that the observed RT data may be explained just as well by attentional mechanisms. Stimuli consisting of pairs of letters produce a temporary facilitation in the stimulus processing of items which share the same pathway (Posner and Snyder 1975). This can be illustrated by their finding that two different letters are matched about 14 msec faster when one of the letters was precued. Consequently, in the case where the two letters were identical, matching is even done much faster (namely 85 msec). Since we did not observe any stronger facilitation of identical pairs in the precue conditions than in the full choice condition, we doubt whether in the present experiment identical letter pairs are recognized faster than non-identical pairs.

The better known Sternberg et al. (1978) paradigms to identify the unit, i.e. using the RT increase and the increase of movement duration per unit of 10 msec per unit contained in a sequence, could not be employed fully since the number of units, as it turned out, was constantly two. One may doubt whether these paradigms are in fact as applicable in handwriting patterns as they are in speech and in typing. For instance, Hulstijn and Van Galen (1983) found no evidence for any subdivision of their letter-writing sequences into two or more units. Furthermore Wing's (1978) data on simple RT and movement duration per stroke in the zig-zag letters *v*, *u*, *w*, *m* did not show the characteristic behavior which would be expected if one stroke formed a unit. A more elaborate experiment by Stelmach et al. (1983), generally confirmed Wing's data. However, Van Galen and Teulings (in prep.) found some evidence of units being individual strokes in a similar paradigm. Their patterns consisted of geometric figures of one or two straight lines. According to various other criteria, one could propose that strokes may form units in handwriting (Maarse and Thomassen 1983) or in handwriting-like patterns (Thomassen and Teulings 1983), since they may show independent transformations. Wing (1978) proposed an up-down stroke pair as a unit, which was based on the positive correlation of their durations. This may, however, be an artifact of a mechanical constraint or even of a learned movement grammar that tries to maintain a constant base line. In addition to the differences in the criterion used, a possible explanation for the inconsistence of the various proposals as to what is the size of a unit in handwriting may be the view that the subjects organize their movements into chunks – a single letter in the present experiment – such that four different chunks are enough to produce all possible patterns in the design by combining just two chunks.

The present results corroborate a model containing a long-term motor memory and a short-term motor buffer, each having different properties. When in choice conditions the long-term motor memory has been accessed in order to retrieve a certain specific movement pattern, the same pattern can be retrieved faster the second time. Apparently, the interval between two accesses plays a minor role: the RT reduction in identical patterns is also found in the precue second condition in which the second letter can be retrieved more than 1 sec before the preceding letter. Probably an analogous effect is present when the subject repeats the same trial within several seconds (Van Galen 1980). Complex drawing patterns showed 30 to 50 msec faster choice RTs in trials that occurred as the first repetition in a run, with no further reduction on the second repetition. In less complex patterns, containing only a single stroke, however, the repetition effect appeared to be absent in the latter study.

The reason why the RT reduction is less pronounced in the precue first condition is probably a floor effect of the RT or the fact that the subject already knew the first two or four strokes preceding the connection stroke (i.e. about 240 or 480 msec, respectively) so that the subject might have initiated the movement while preparing the second letter (cf. Hulstijn and Van Galen 1983). The small difference between the precue first condition and the simple condition may illustrate that a little advance preparation is still taking place.

In the simple condition the long-term motor memory retrieval process may be completed before the imperative stimulus occurs. The movement information is stored in a short-term buffer (cf. Sternberg et al. 1978). The short-term buffer retrieval process is governed by another set of rules: It is supposed to be a self-terminating sequential search through a nonshrinking buffer. The buffer contains in a more or less random order a packed copy of each program unit to be executed (irrespective of whether they are identical of not). Therefore no gain of RT needs to be expected in identical patterns; instead RT and movement duration per unit should increase with the number of units in the sequence. Empirically it has been shown that movement duration is also increased when the units in the sequence are identical.

Note that it has been assumed that the units identified in the short-term buffer need not to be as large as the units that can be identified in the long-term motor memory although we have not found any discrepancy between units in both levels. The finding that the movement durations of writing patterns do not seem to depend strongly upon the way the pattern has been prepared is also found by Stelmach and Teulings (1983). This gives rise to the speculation that in choice conditions the same long-term motor memory retrieval process and short-term buffer retrieval process are involved as in the simple condition, and that in continuous movements that are planned and executed in overlapping sequences, both retrieval processes are active at the same time.

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Discussion

Units of Movement

The results of our experiment indicate that complete allographs may form 'movement units' in long-term motor memory. However, the extent of the units of movement is probably not absolute but may depend upon three kinds of circumstances. First, it may depend upon the hierarchical structure of the writing patterns being investigated. If the set of writing patterns in an experiment does not give rise to any hierarchical structure, but merely consists of various sequences of strokes, no clear units may be definable. Any duration effects will then appear to become so small, that they are undetectable due to the limiting factor of the speed of the peripheral part of the motor system (Teulings, et al., 1986). Secondly, it may depend upon the processing level being investigated. The conclusions of our investigation might only hold at the allographic motor-memory level. This is just one of the levels distinguished by Van Galen, et al., (1988) in their handwriting model. They distinguished linguistic, semantic, allographic, and motor-programming levels. Van Galen et al. assumed that the lower in the hierarchy, the smaller the organizational unit. Thirdly, the extent and also detectability of the unit will depend upon the level of practice (Hulstijn & Van Galen, 1988). Although these authors confirmed some of the well-known reaction-time effects of the number of possible units in unfamiliar writing patterns, the effects were hardly detectable in familiar writing patterns. This might indicate that units in handwriting cannot be defined unambiguously by using absolute indicator values (such as a 10-ms reaction-time increase for each unit in the sequence). However, the conclusions of our experiment on familiar patterns are largely independent of the level of practice: they are only based on comparisons of the relative strengths of two effects. That the effects may become zero after extended practice just highlights the motor system's flexibility in the organization of its memory.

Memory-Retrieval Models

The paradigm employed in our experiment was suggested by various empirical reaction-time and movement-time data, which were collected to support a specific memory-retrieval model by Sternberg et al. (1978). This model comprises Von-Neumann-computer metaphors such as sequential processing, buffering, and buffer searching. Similar sequential-stage models are Ellis' (1982) writing-and-speaking model and the classical multi-stage stimulus-processing and response-generation model (e.g., Sanders, 1980). Since then, various relevant models on how movement information is retrieved from a memory, have been introduced. These models have in common that they assume a parallel processing structure instead of a serial one. The first type of model still incorporates sequential processing levels, but they overlap in time (Harrington & Haaland, 1987, on hand movements; Van Galen et al., 1986, on handwriting; Klapp & Wyatt, 1976, and Garcia-Colera & Semjen, 1987, on finger tapping). According to these partly parallel models, only the initial part, the movement pattern, is processed strictly sequentially. Another model, based on finger tapping (Rosenbaum et al., 1984) provides an alternative for Sternberg's et al. buffer-searching model. According to Rosenbaum's et al. *hierarchical-editor model* a sequence of movements is hierachically organized. The procedure of movement initiation and movement execution can be visualized as a two-pass tree-traversal process. Both latency and interunit times of a sequence of movement units are related to the length of the node path leading from the top node to the terminal node. This model predicts similar reaction-time and movement-time effects as the model by Sternberg et al. (1978). For instance, long sequences are produced at a lower rate than short sequences. A similar tree-traversal structure is proposed for the selection of the movement in choice-reaction time. An important model is Rumelhart and Norman's (1982) model of typewriting simulation and might perhaps be applied to handwriting as well. Their model accounts for a set of competing schemata, each of which specifying the movement to hit a specific key. The activation of each schema is raised or lowered by various processes. The most activated one is executed. A modern type of model of a 'memory retrieval process' in handwriting, has been presented by Morasso and Mussa Ivaldi (1987). Movement information can be stored in a *Kinematic Network*, by associating alphabetical input patterns and motoric output patterns directly. In fact, this type of model is an implementation of the *recall schema* in the *schema theory* (Schmidt, 1975). During exercise of, for instance, a linear positioning movement, the recall schema associates two things: on the one hand the relation between external movement outcome and initial conditions, and on the other the internal movement parameters. According to this theory, variation of intended movement outcome and initial condition 'calibrates' the recall schema within the range of variation. However, none of the latter models provides a paradigm to investigate the extent or even existence of a 'memory unit', though some models do assume specific units.

Slowing down of identical units

A particular paradigm exploited in our investigation, was suggested by the observation that the execution speed is slower in sequences of identical units than of nonidentical ones. None of the previous models is explicit on possible sources of this phenomenon. Only the Sternberg et al. (1978) model may suggest that identical units in a buffer are subject to confusion. Although lacking a definite explanation, the slowing down of repetitive sequences must have a general origin because it has been observed in various types of movements, for instance, in speech at the word level (Sternberg et al., 1978) and in handwriting at the character level (this chapter; Wing et al., 1979; Van Galen et al., 1988). Although a similar effect has been found in skilled typing (Gentner, 1987), this is probably due to the additional requirement of lifting the finger before hitting the key again. Wing et al. used the slowing down of handwriting, to show that allographs of two different sizes still acted as the same unit. This finding supports our assumption that size is an irrelevant parameter at the motor-memory level. They also showed that two different forms (allographs) of the same characters act as different units. This finding supports the notion that below the linguistic level another level exists with shape as a key feature. The results by Van Galen et al. are interesting in that they demonstrate the slowing down of repetitions in normal handwriting as well. These authors attribute the slowing down to increased visual monitoring requirements, because the effect is amplified under visual deprivation. Indeed, visual monitoring is relevant in producing the correct number of strokes and characters in words with repeated strokes or characters (Lebrun & Rubio, 1972). However, the same kind of repetition errors are also produced if the writer exerts normal visual guidance, but performs some unrelated counting task simultaneously (Smyth & Silvers, 1987). This indicates that the slowing down of repetitive sequences is not only caused by the increased difficulty of visual monitoring. Errors are more likely, moreover, when writing the same Japanese or Chinese character repeatedly at a high rate (Nihei, 1986). The important result of the latter investigation was that the errors yield other characters which are either motorically or phonetically related. This observation is consistent with the observation that 95% of the *slips of the pen* in Western handwriting yield another character rather than nonexistent combinations of strokes (Van Nes, 1971; Ellis, 1982). Although these findings may indicate that the organization of motor memory in handwriting is probably hard to separate from its higher-order, linguistic level, they support the result of the present study, viz., that allographs constitute the organizational units of the long-term motor memory in handwriting.

CHAPTER 4. BIOMECHANICAL EFFECTS

In the preceding chapter, various neural mechanisms, located at the central level of the motor system, have been discussed. The present chapter pays attention to the peripheral part of the motor system: the handwriting apparatus, a biomechanical system consisting of limbs and fingers, joints and muscles. As the information flow is from the central to the peripheral level, it seems appropriate to discuss the central level first. Arguments for first investigating the peripheral level are, however, valid. In investigating the motor system, a 'view' of the central level of the motor system may be obtained only via the peripheral level, which is, by necessity, always involved in movement execution. This view could thus be obscured at the peripheral level because of neuromuscular limitations. For example, the time taken to execute the simplest movements depends mainly upon the time required for muscle contraction: a single-phasic (arm) movement is rarely shorter than 100 ms and during this period the planned movement does not appear to be modified by proprioceptive feedback (Wadman et al., 1979, 1980). Similarly, in skilled typewriting, repeated single-finger keystrokes (actually two-phasic movements) do not take less than 100 ms (Gentner, 1983). In rapid speech, the duration of a syllable is also at least of the order of 100 ms (Sternberg et al., 1978). Finally, in handwriting movements, stroke durations are typically 100 ms (this chapter). These data imply that the peripheral part of the motor system could be the limiting factor determining the maximum rate of movement production, and thus obscure any duration effects at the central level of the motor system. Knowledge of the peripheral level of the motor system would therefore seem to be a precondition for understanding the central level.

However, the arguments to present the peripheral level at this late stage carry more weight. The main argument is that the peripheral level of the handwriting motor system is extremely difficult to understand because the mechanical description of the entire biomechanical handwriting apparatus is very complicated. In the shoulder-elbow system, with only two degrees of freedom allowed, Morasso (1981) found that fast hand movements show single-peaked velocity curves, whereas the angular-velocity curves of the individual joints have a more complex appearance, which even depends upon movement direction. Morasso concluded that movements are coded in terms of an external frame of reference at the central level rather than in terms of joint rotations. This implies a most convenient simplification of the motor system: the peripheral level plays no decisive role in determining the spatio-temporal trajectory and does not need to be analyzed prior to studying the central level.

In contrast, when movements are studied in more detail, various direction-dependent properties are found. For instance, investigation of the speed-accuracy trade-off in joy-stick movements in the Fitts paradigm shows that movements in horizontal and vertical directions are faster than those in diagonal directions (Jagacinski & Monk, 1985). Similarly, studies of the shape of the trajectory of compound shoulder-joint and elbow-joint movements, reveal that the latter is curved rather than straight. This curvature is attributed to the measured time lag between initiation of the rotations in shoulder and elbow (Wadman et al., 1980), a lag varying with movement direction (Kaminski & Gentile, 1986). The latter authors showed, however, that the departure from straightness cannot be completely explained by the measured time lag. Their data suggest that biomechanical factors contribute to trajectory non-linearities.

A more fundamental description of hand trajectories as a function of biomechanical properties of the arm is based on static measurements of the elasticity and viscosity coefficients of the shoulder and elbow joints (Hogan, 1985; Flash, 1987). Flash, basing himself upon these measurements, could very accurately simulate the curvature of the recorded hand trajectories as a function of movement direction. Measurements of this kind are not easy to perform in the handwriting apparatus. In spite of the fact, that encouraging attempts to measure elasticity coefficients, disregarding individual joints or directional properties, have been performed (Denier van der Gon & Thuring, 1965; Vincken & Denier van der Gon, 1985), the conclusion is that a biomechanical model of the handwriting apparatus remains difficult to evaluate quantitatively. The research reported in the article forming the core of the present chapter is therefore a descriptive study of some properties of the handwriting apparatus as a function of movement direction, without attempting to provide a complete account in terms of joint mechanics.

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A DESCRIPTION OF HANDWRITING IN TERMS OF MAIN AXES

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ABSTRACT

The handwriting apparatus has no symmetries, which indicates that its biomechanical properties are likely to vary with movement direction It has been argued that, disregarding arm or pen-lift movements, the handwriting apparatus can be described in terms of three degrees of freedom one corresponding to the wrist-joint movements, and the other two to the finger-joint movements. The present study demonstrates that four movement directions with characteristic properties, following two orthogonal main axes, can be distinguished Wrist-joint movements show short stroke durations and small spatial error (i e , departure from a straight stroke), whereas finger-joint movements have long stroke durations and relatively small spatial error Movements in intermediate directions typically have intermediate stroke durations and large spatial error However, neither of these main axes correspond to the 'horizontal' base-line in normal handwriting nor to the direction of the most frequent downward movements, reflecting the slant of handwriting Only the direction of the most frequent up-forward movement is similar, but probably not identical to, the main axis that is characterized by the fast and accurate wrist-joint movements Main axes in handwriting appear to be useful at the descriptive level of the handwriting movement but probably not at the internal level of movement representation This conclusion is based on the failure to find systematic force-onset asynchronies or differing force-versus-time curves between both main axes, which could have explained the specific behavior of spatial error.

INTRODUCTION

The handwriting apparatus has no symmetries, indicating that its biomechanical properties are likely to vary with movement direction. The notion that direction of movement affects duration per stroke, has been reported as early as 1900 by McAllister [9]. Back-and-forth movements with the right hand in an upward direction to the right (i.e., wrist-joint movements) took 33 units of time, whereas movements in a perpendicular direction (i.e., finger-joint movements) took 43 units of time. The movement-time data by McAllister, suggest that wrist-joint movements and finger-joint movements correspond to main axes with characteristic properties: wrist-joint movements are fast and finger-joint movements are slow whereas movements in intermediate directions have intermediate stroke durations. It should be realized that the term main axis does not refer to the biomechanical axis of rotation but rather to the movement directions in the writing surface showing special properties. This paper intends to confirm these findings and to investigate whether any other direction-dependent properties of the handwriting apparatus can be found.

The idea of main axes is not new. Denier van der Gon and Thuring [2], basing themselves on selective neural disturbances, referred to horizontal and vertical axes, according to which movements might be organized. Dooijes [3] used nonorthogonal,

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Footnote. This research was supported by ESPRIT Project 419 "Image and Movement Understanding".

horizontally translating axes ("principal directions"). One axis was chosen parallel to the voluntary wrist-joint movements and the other parallel to the movements of the upper two phalanges of the index finger. Dooijes found these axes to be reproducible even after a year, suggesting their biomechanical origin. Similarly, Plamondon and Lamarche [13] estimated main axes ("principal axes" or "natural axes") by asking subjects to perform wrist-joint movements and finger-joint movements separately. Maarse, Schomaker and Thomassen [7] assumed that normal handwriting is produced by two separate subsystems; one consisting of the thumb and the fingers, the other of the entire hand rotating around the wrist. They determined the directions of wrist or finger movements by asking the subjects to perform small wrist or finger movements under various levels of wrist-joint rotation. However, the direction of the finger movements did not vary with arm orientation, which suggests that main axes cannot be estimated reliably by just asking the subjects to perform finger movements. In addition they found that, although the two systems differ considerably with respect to their inertia, their preferred or maximum oscillation frequencies did not. Questions as to how the nervous system is able to control a single-joint multi-muscle system have been the object of more fundamental study. For example, Ostriker, Pellionisz, and Llinas [10] noticed that eye-movement trajectories parallel to the characteristic movement directions ("eigen-directions"), show less error than those in other directions. Soechting and Ross [14] simply hypothesized "that the 'natural' coordinate representation of joint angles would be the one in which the standard deviation in the difference between joint angles of the two limbs would be least" (p. 596).

In order to evaluate criteria for identifying main axes in handwriting movements, it is necessary to take a closer look at the degrees of freedom of the handwriting apparatus. Let us approximate the joints of the handwriting apparatus as hinge-like or universal joints (see De Lange [1] for a more detailed description of the wrist joint). Each hinge-like joint has one degree of freedom and each universal joint two degrees of freedom. Neglecting forearm movements, the writing apparatus has at least ten degrees of freedom. The wrist joint amounts to two degrees of freedom (dorsal/palmar flexion and ulnar/radial abduction). The thumb and the index finger each possess four degrees of freedom: one degree of freedom for each of the two peripheral finger joints (flexion/extension), and two degrees of freedom for the proximal one (flexion/extension and adduction/abduction). The other fingers move like the index finger and therefore do not contribute to the degrees of freedom of the handwriting apparatus. However, not all passive or theoretical degrees of freedom are used in handwriting. For instance, the most peripheral joint of the index finger cannot be controlled independently, pen grip requires that thumb and fingers be kept opposed, and the pen tip has to touch the paper. Thus the wrist joint uses only one degree of freedom (combination of palmar flexion and radial abduction/dorsal flexion and ulnar abduction, depending upon the level of supination/pronation of the forearm). The thumb-and-finger system uses two degrees of freedom: small movements to and from the hand palm (by flexion/extension of both thumb-joints and finger-joints) and, independently from that, back-and-forth movements parallel to the hand (by simultaneous flexion/extension of thumb-joints and the extension/flexion of finger-joints). Therefore, handwriting movements, requiring both wrist-joint and finger-joint movements, employ only three degrees of freedom.

To what extent are handwriting movements affected by coordination inaccuracies of the muscle systems involved? In movements that can be performed using a single degree of freedom, inaccuracies result only in departures within the trajectory itself (i.e., in the position-versus-time relation) and not in departures from the planned trajectory. However, handwriting movements that are performed using two degrees of freedom require the coordination between the two synergistic muscle systems. For example, a straight stroke will become distorted if the delays for activating the two synergistic muscle systems are not equally anticipated (resulting in curved stroke endings) or if their force-versus-time patterns are not proportional (resulting in curved strokes). Movements using three degrees of freedom reach end positions in the two-dimensional plane by a range of combinations of the end positions of each of the degrees of freedom (e.g., [11]). Therefore, the spatial error of strokes, especially that of the end positions, may be increased. In other words the more degrees of freedom involved the larger the departure from the planned trajectory. According to the preceding analysis of degrees of freedom, wrist-joint movements allow the production of the most accurate trajectory. Finger-joint movements produce the trajectory less accurately. Finally, movements requiring both wrist-joint movements and finger-joint movements produce the trajectory least accurately. Thus, apart from the extreme stroke-duration criterion previously mentioned, this minimal spatial-error criterion may be another appropriate criterion to estimate main axes in handwriting movements. In fact, at least four characteristic movement directions can be distinguished using either criterion. The present research intends to verify whether both criteria yield consistent, characteristic directions, and whether the characteristic directions form opposite pairs. This would provide evidence that the description of handwriting movements in terms of main axes is appropriate.

How can we measure spatial error of a planned handwriting movement? The problem is that the higher-order internal representation of the movement to be executed is unknown. Only short, straight trajectories more or less parallel to a certain direction seem feasible because the trajectory can satisfy the highest requirements with respect to straightness even if the direction is not exact. However, wrist-joint movements in adults will not produce a perfectly straight trajectory but rather a circular trajectory with a radius of about 150 mm. However, the circular trajectory may only be expected to occur in one specific movement direction which is not a priori known. Therefore, it seems best to fit a straight line through each stroke. The RMS distance of the samples to the line may be a measure for the spatial error. In small stroke lengths, which are typical for handwriting (e.g., 10 mm), the RMS distance between a small arc segment, with radius of 150 mm, and a straight line is small anyway (i.e., 0.031 mm) [3]. A handwriting pattern that allows the simultaneous measurement of stroke duration and of spatial error consists of a sequence of fast, short, straight back-and-forth movements, as investigated by McAllister [9]. Any other pattern would be less appropriate. For instance, isolated movements, would be less representative of handwriting, and handwriting-like sequences with various movement directions would be too complicated to perform. However, the back-and-forth nature of the chosen pattern creates a problem in balancing the properties between the back and the forth stroke. Different properties of strokes in opposed directions are likely because they are produced by different synergistic muscles. This lack of symmetry may cause characteristic directions to form nonopposed pairs, which would be inconsistent with a simple description in terms of main axes.

If the hypothesized main axes exist, what then is their relation to various other specific directions in normal handwriting? The first question is whether one of the hypothesized main axes corresponds to the 'horizontal' axis (i.e., the direction of the base-line or of the horizontal progression). Another relevant direction is the slant of handwriting. The slant, normally slightly steeper than the direction of the most frequent downward strokes, appears to be rather invariant under various levels of horizontal-progression speed [8]. Finally, what is the relation between main axes and the most frequent movements in handwriting? In order to answer these

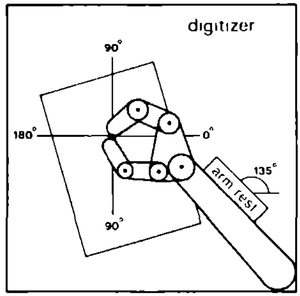

Figure 1. The subject's arm was immobilized using an arm rest at an inclination of 135 degrees In the back-and-forth task a rosette at the preferred position indicated the movement directions In the normal-writing task, paper orientation and base-line orientation were free. Dots indicate wrist joints and finger joints in the idealized hand

questions, we recorded the subjects' normal handwriting to estimate base-lines and prevailing movement directions.

EXPERIMENT

An experiment was carried out in which subjects performed trials of fast, small back-and-forth movements in a number of orientations. It should be noted that the back-and-forth movements of one trial yield two opposite (not necessarily dependent) movement directions for that trial. The two directions were treated separately. Variables of interest were across-trial average duration, and spatial error per stroke (i.e., its departure from a straight trajectory). Recordings of the subject's normal handwriting were made in order to estimate the base-line and the most frequently occurring movement directions.

Subjects

Thirteen adult, right-handed, male and female students with arbitrary style of handwriting (e.g., cursive or handprint, slanted or upright, etc.) volunteered for the experiment.

Apparatus and Materials

A computer-controlled digitizer (CalComp 924GB) and pen (laboratory made) were used to record handwriting in terms of horizontal and vertical coordinates and axial pen pressure, at a sampling rate of 105 Hz. The coordinates had an RMS accuracy of 0.1 mm [10]. The axial pen pressure served as a sensitive switch to detect lifting or lowering of the pen. The subject's right forearm rested completely on the digitizer and was practically immobilized by an arm rest with an inclination of 135 degrees relative to the front of the digitizer (see Figure 1). The digitizer as a whole could be rotated in order to obtain a comfortable arm position.

Handwriting Patterns and Procedure

Each subject performed two different tasks within a 20-minute session. One task was to copy as much of a 40-character Dutch sentence as possible in 19 seconds. The other was the production of short back-and-forth movements (approximately 10

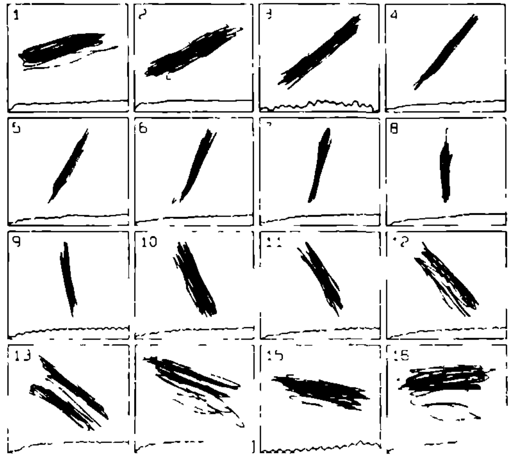

Figure 2. The recordings of the second replication of the back-and-forth tasks by Subject 1 The numbers correspond to the target directions of Figure 5. Below each pattern, the axial pen pressure is plotted as a function of time.

mm long) for 4 seconds in each of 16 equidistant orientations in random order, yielding 32 directions separated by 11.25 degrees. The tasks were then repeated in reversed order. The subjects were instructed to write at comfortable speed.

In the back-and-forth task, the subjects wrote on an overhead sheet which was placed on top of a rosette, indicating the 16 target orientations (see Figures 2 and 5). The functions of the overhead sheet were (i) to maintain a permanently clear view of the rosette consisting of the target orientations, (ii) to minimize visual feedback (because the pen produced only a faint line), and (iii) to minimize pen-paper friction. Pen-paper friction consists of static friction, causing the pen to decelerate and to accelerate abruptly at velocity minima. The friction possibly hides interesting distortions due to the coordination difficulties at the beginning and at the end of a stroke. The subjects were instructed to perform the movements at a comfortable speed. Every four-seconds recording could then be inspected and compared with the target orientation on a graphical display. The digitizer hardware did not sample the horizontal and vertical coordinates simultaneously. In order to obtain appropriate position estimates, one coordinate was delayed artificially [15]. Without this correction, straight movements, diagonally oriented with respect to the digitizer's coordinate system, would seem systematically distorted. In the recording of normal handwriting the subject was instructed not to move his, or her, forearm. Instead, the paper was to be repositioned by the subject's left hand (see Figure 3). The subjects could do this without disrupting the normal writing movement.

Analysis

For each four-second trial of back-and-forth movements, the movement data were lowpass filtered, differentiated, and segmented on the basis of minima in the absolute velocity, yielding separate 'strokes' [15]. The filtering was necessary in

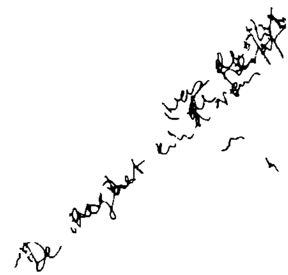

Figure 3 The recording of the first replication of the normal-handwriting task by Subject 1 Words seem to be superimposed in the recording because the subject had to reposition the paper as the arm was immobilized Dotted trajectories indicate movements while the pen was not touching the paper A 1 cm calibration is given

order to estimate departures from the fitted line, which could be smaller than the quantization distance of the digitizer Stroke duration was estimated by the time difference between successive segmentation points Spatial error per stroke was estimated by the average RMS distance across samples with respect to the minimal-squares line Stroke length was estimated by the distance between successive segmentation points Medians were determined, based on all strokes within the 4-seconds recordings in each of the 32 directions The base-line direction for each recording of normal handwriting was estimated using the frequency distribution of all vectors between the absolute-velocity minima i and i+4 where the pen is on paper (32 histogram classes) Each vector is an estimate of the base-line as, after four strokes, the pen will often be at the same height relative to the base-line The direction which occurs most frequently is an estimate of the base-line direction Finally, the frequency distribution of written movement directions was estimated (32 histogram classes) Each replication of a task yielded 32 data, which had to be lowpass filtered (see Footnote 1)

Footnote 1 The sets of 32 (circular) data were lowpass filtered using a cosine transition band such that oscillations of more than 10 periods were suppressed completely and of less than 2 periods not at all It is not likely that this filtering introduces non existing opposite or orthogonal minima For instance, the 2 periods oscillation introduces minima at opposite directions (i e , with distances of 180 degrees) but not necessarily in the presence of the 1 period or the 3 periods oscillation (which are suppressed by factors 1 and only 0 96, respectively) Similarly, the 4 periods oscillation (which is already suppressed by factor 0 85) introduces minima at orthogonal directions (i e with distances of 90 degrees) but not necessarily in the presence of the 2-periods or the 6 periods oscillation (which are suppressed by factors 1 and only 0 50, respectively) Furthermore, the analysis assumed equidistant data As the subjects appeared to keep the deviation of the actual direction from the target direction within 7 degrees , the actual movement direction was taken to be equal to the target direction Maxima and minima were determined on the basis of a fitted parabola

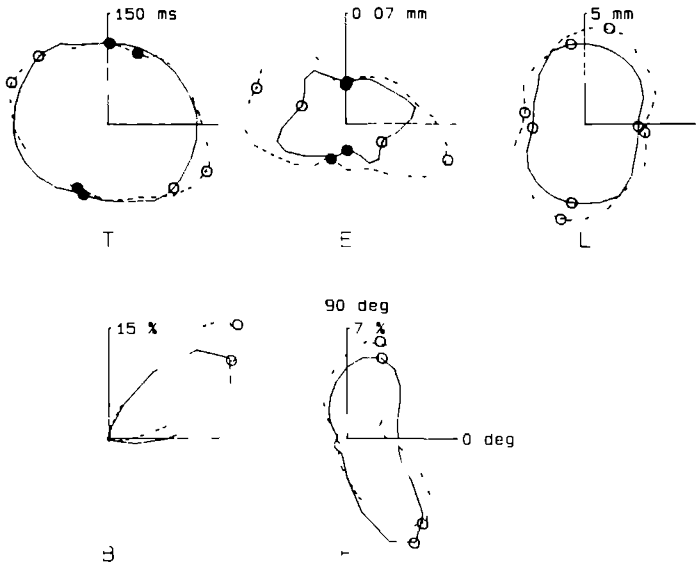

Figure 4 Polar representations of the two replications of the tasks by Subject 1. The second replication is dashed Stroke duration (T), spatial error (E), and stroke length (L) as a function of direction, have been estimated by medians per trial in the back-and-forth movement task Frequency distributions of base-line estimates (B), and movement directions (F) as a function of direction have been determined in the normal-handwriting task The directions marked with circles show extreme stroke durations or stroke lengths, relative minimal spatial error, or maximal frequency Filled circles refer to wrist-joint movements

RESULTS

Figure 4 shows an example of the polar representations of stroke duration, spatial error, and length per stroke as a function of movement direction in the back-and-forth task. The distribution of base-line estimates and the frequency distribution of movement directions in normal handwriting, have also been depicted. Characteristic directions having extreme (i.e., minimal or maximal) stroke duration or minimal spatial error have been marked. Similarly, the directions with minimal or maximal stroke lengths have been marked, as well as the most likely base-line direction and the most frequent movement directions. Due to noise in the spatial-error data no local minimum could be detected on top of a peak (which is bimodal, in general) in 13 out of 96 cases. In the latter cases, the direction of the expected relative minimum is, therefore, best estimated from the direction of the maximum.

Table 1 presents the four characteristic directions per subject, determined by the extreme stroke-duration criterion and the minimal spatial-error criterion. The directions of the most likely base-line and the most frequent movement directions are included. The characteristic directions were manually assigned to wrist-joint versus finger-joint, and flexion versus extension movements, using the assumption that wrist-joint movements have directions approximately orthogonal to the forearm orientation [7]. Figure 5 shows the average directions in a polar representation. It appears that the characteristic directions defined by the extreme stroke-duration criterion and by the minimal spatial-error criterion tend to coincide (3 Wilcoxon

Table 1

The four characteristic directions per subject based on the extreme stroke-duration criterion (T) and the minimal spatial-error criterion (E) plus the most likely base-line directions (B) and the most frequent movement directions (F). Zero degrees represents a rightward direction. A positive value represents an upward and a negative a downward direction.

	Characteristic direction											
	Wrist-joint						Finger-joint					
	Flexion		Extension				Flexion			Extension		
Subj	T (deg)	E (deg)	T (deg)	E (deg)	F (deg)	B (deg)	T (deg)	E (deg)	F (deg)	T (deg)	E (deg)
1	-112	-99	78	89	69	37	-34	-23	-53	148	158
2	-60	-88	27	24	45	15	-11	-16	-98	169	161
3	-101	-109	67	46	86	46	-2	-33	-53	181	149
4	-103	-130	71	45	70	-1	-16	-36	-77	159	135
5	-104	-113	55	50	67	9	-2	-17	-86	168	151
6	-83	-104	64	70	82	42	-8	6	-47	169	142
7	-93	-107	66	54	69	44	-22	-14	-89	183	131
8	-139	-121	95	54	74	38	9	-56	-76	161	122
9	-85	-107	90	105	95	38	1	-14	-47	184	183
10	-120	-129	59	77	112	34	1	13	-42	180	135
11	-134	-132	57	60	77	39	-2	-31	-68	157	135
12	-131	-123	100	68	86	46	-18	-13	-53	166	154
13	-50	-95	126	77	86	46	-1	-1	-53	173	171
mean	-101	-112	73	63	78	33	-8	-18	-65	169	148
sd	27	14	25	21	16	16	12	18	18	11	17

matched-pairs signed-ranks tests, $N=13$, $T \geq 17$, $p \geq 0.05$). An exception was the difference between the characteristic directions corresponding to the finger-joint extension movements (having means of 169 and 148 degrees, respectively) ($N=13$, $T=4$, $p<0.01$). The latter movement direction occurs only rarely in handwriting [8]. Nonsignificant differences could also have been produced by random data. However, the characteristic directions defined by the extreme stroke-duration criterion and the minimal spatial-error criterion appear to correlate positively for the wrist-joint flexions (Spearman's $r=0.76$, $N=13$, $p<0.01$), though nonsignificantly for the wrist-joint extension ($r=0.41$, $p>0.05$), finger-joint flexions ($r=0.05$, $p>0.05$) and the finger-joint extension ($r=0.17$, $p>0.05$). So there is marginal evidence that both criteria yield consistent results.

The characteristic directions defined by the extreme stroke-duration criterion form opposite (2 tests, $N=13$, $T>32$, $p>0.05$) and orthogonal pairs (4 tests, $N=13$, $T>27$, $p>0.05$). The same holds for the characteristic directions defined by the minimal spatial-error criterion (4 tests, $N=13$, $T>27$, $p>0.05$), with the exception of the finger-joint extension movements (having a mean of 148 degrees) which do not form an opposite pair and only one orthogonal pair (2 tests, $N=13$, $T<15$, $p<0.05$). These results taken together do not preclude the notion of opposing, or orthogonal characteristic directions. This implies that orthogonal main axes may be useful in describing the properties of the handwriting apparatus.

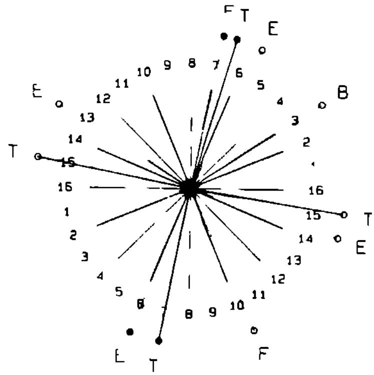

Figure 5 Rosette of directions (1 to 16) of movements used in the back-and-forth task and as bins in the frequency distribution estimates, plus the characteristic directions defined by the extreme stroke duration criterion (T), the minimal spatial-error criterion (L), the direction of the most likely base-line (B), and the most frequent movement directions (F) Filled circles refer to wrist-joint movements

The estimated base-line direction differs from any of the characteristic directions found with the extreme stroke-duration or the minimal spatial-error criterion (8 tests, N=13, T=1, p<0.01) Similarly, the direction of the most frequent downward movements differs from any of the characteristic directions found (8 tests, N=13, T=0, p<0 01). The direction of the most frequent up-forward movements seems to correspond marginally to those of the wrist-joint extensions: no difference according to the extreme stroke-duration criterion (N=13, T=36, p>0 05) but a significant difference according to the minimal spatial-error criterion (N=13, T=11, p<0.02) Their correlations show the opposite picture (Spearman's r=0.43, N=13, p>0 05; r=0 59, N=13, p<0 05, respectively). In other words, the most frequent forward movement direction in handwriting is close to, but probably not identical to, the direction of wrist-joint extensions.

The values belonging to the directions, listed in Table 1, have been presented in Table 2 In accordance with the way the data have been arranged, the wrist-joint movements yield smaller stroke durations than the finger-joint movements (4 tests, N=13, T=0, p<0 01). The same holds for the spatial error (4 tests, N=13, T≤17, p<0 05) No differences in stroke durations or spatial error were found between opposite characteristic directions (4 tests, N=13, T>32, p>0.05). This confirms our expectation that two main axes with different properties exist. one corresponding to wrist-joint movements which are not only fast but also accurate, and the other to finger-joint movements which are slow but less accurate. Movements with directions between both axes are executed at an intermediate speed and are least accurate.

Factors Determining Spatial Error

The directions characterized by the smallest spatial errors (of the order of 0.04 mm) correspond to those with the greatest stroke lengths (9±4.5 mm), and the directions characterized by the somewhat greater spatial errors to those with the smallest stroke lengths (6±3 mm). Under the assumption that the 9-mm strokes have been produced by wrist-joint movements, a substantial part of their spatial error is an artifact due to the linear approximation of their circular trajectories (e.g., 0.03

Table 2

The values of stroke duration (T), and spatial error (E), of the four characteristic directions per subject listed in Table 1, plus those of the density of the base-line estimates (B) and the movement direction frequencies (F) in normal handwriting (in percentages per bin of 11.25 degrees).

	Characteristic values										
	Wrist-joint						Finger-joint				
	Flexion		Extension				Flexion			Extension	
	T (ms)	E (.001mm)	T (ms)	E (.001mm)	F %	B %	T (ms)	E (.001mm)	F %	T (ms)	E (.001mm)
Subj											
1	98	20	106	25	6	22	137	47	8	136	45
2	86	31	87	26	6	17	95	29	7	94	26
3	90	87	91	69	7	16	146	74	8	137	52
4	103	34	105	28	6	12	121	46	7	126	41
5	135	31	140	27	5	14	186	84	8	168	86
6	104	15	102	20	4	14	127	26	7	128	24
7	102	41	100	26	9	20	130	71	7	131	35
8	260	68	255	62	8	16	304	73	6	348	71
9	100	31	94	44	6	11	192	146	8	199	255
10	127	111	138	103	5	14	147	96	7	157	131
11	126	33	121	46	7	13	148	52	7	138	34
12	102	15	100	16	7	16	130	37	8	127	39
13	209	49	210	44	7	16	259	166	8	264	121
mean	126	44	127	41	6	16	163	73	7	166	74
sd	51	29	50	25	1	3	59	43	1	69	64

mm in 10-mm strokes). Therefore the spatial errors of the wrist-joint movements will be even smaller than stated. In spite of that, the corresponding directions could be identified unambiguously, implying that the linear approximation satisfies.

Two main axes have been identified by their characteristic movement properties. Could handwriting be the result of two independent component-movements along these main axes? If so, the error due to the coordination inaccuracies of the two main-axis components will introduce spatial errors in a short, straight stroke. The raw data can be used to shed light upon the type of coordination error in the motor system. This is the purpose of the following analysis. Spatial error could be caused by systematic differences in force-versus-time relations of the muscle systems, i.e., by differences in the corresponding component position-versus-time relations per main axis (although the moments of movement onset may be appropriate). However, the raw data show that component position-versus-time relations are very similar in all directions. At any rate, we did not succeed in consistently decomposing position-versus-time curves of arbitrary movement directions into those belonging to any pair of possible main axes. This failure holds if back and forth movement directions were distinguished and stroke durations normalized.

Spatial error could also have been introduced by systematic differences in movement onsets between both main axes (i.e., phase differences other than 0 or 180 degrees, the position-versus-time relations being equal). Systematic phase differences may easily be caused by inappropriately anticipated nerve-conduction or muscle-activation delays per synergistic muscle system A phase difference can be detected by testing whether the velocity shows a systematic leftward or rightward loop at the beginning of a stroke, especially in movement directions where both main axes are equally involved and friction is low However, the data show that the velocity vector has no systematic component to the left or to the right at the segmentation points in any subject There is, however, a tendency towards narrow rightward loops instead of perfect back-and-forth movements in directions close to the wrist-joint axis This may be due to some small hysteresis or to imperfect correction for nonsimultaneous sampling which becomes manifest in the extremely accurate wrist-joint movements Our conclusion in this analysis is that the spatial error is probably due to non-predictable, random variations of the component movements This implies that the motor system is surprisingly well balanced on the output side, considering the large variety of muscle systems and joints involved Apart from stroke duration and spatial accuracy, no other specific movement-direction properties could be found

DISCUSSION

The experiment reported here shows that the two main axes are useful at the descriptive level of the handwriting movement but probably not at the internal level of movement representation One main axis corresponds to wrist-joint movements, which can be identified in handwriting by their speed and high spatial accuracy The other main axis corresponds to the finger-joint movements, being slow and relatively accurate The finger-joint axis appears to be perpendicular to the wrist-joint axis Movements requiring the coordination of wrist-joint and finger joint movements are reasonably fast but least accurate in space The results based on the finger joint movements appear to be less consistent than those based on the wrist-joint movements This may indicate that the role of the fingers is subject specific, even in handwriting with a fixed forearm position The frequently occurring up-forward movements, which represent the connecting strokes between characters, have a direction which is close to that of the wrist-joint extensions In fact, its direction deviates towards that of the finger-extensions, possibly indicating that the connecting strokes consist of a wrist-joint extension plus a finger-joint extension This sounds reasonable, as wrist-joint extensions generally connect the bottom of one letter to the top of the next The relation between the wrist-joint axis and the most frequent up-forward strokes suggests that wrist-joint and finger joint axes can be roughly estimated in a recording of a subject's normal handwriting It is interesting that the system of main axes does not correspond to the 'horizontal' axis of the base-line, nor to the slant of handwriting The latter relation might have been reasonable as slant is normally slightly steeper than the direction of the frequent downward strokes [8] and is stable across various levels of horizontal-progression speed [8], [18] However, slant can be controlled voluntarily [12] which makes its dependence upon biomechanical main axes unlikely

Do these main axes, based on biomechanical properties of the handwriting apparatus, also exist at the higher levels of the motor system? This could be investigated by verifying whether the endpoints of the ballistic strokes are more invariant [17] in terms of main-axis components, than in terms of the usually employed horizontal and vertical components [14] For example, the two main-axis components, would still be accurately reproduced if a movement pattern were distorted by random phase differences between the main axes However, the lack of any systematic differences in timing between the two axes, is not supporting

Further questions are, which neural mechanisms are responsible for the translation of position information into the activities of each of the muscles involved? The motor system would be efficient if it could program its movements in terms of an invariant frame of coordinates. An interesting approach to this problem employs the analysis of movement representations in terms of external-frame and muscle-frame coordinates in isometric, single-joint contractions. A specific movement can be decomposed into covariant components and contravariant components. Covariant components are defined by perpendicular projections upon all single-joint movement axes, and are therefore independent of the directions and number of the axes. The contravariant components are defined by parallel projection upon all single-muscle movement axes. Thus the resultant vector yields the planned movement and the components represent the physical information needed to perform that movement [11]. In this approach, it is hypothesized that the motor system represents movements in terms of the covariant components. A tensor could do the job of transforming the covariant components into contravariant components. Special movement directions are those where covariant and contravariant components are parallel (i.e., the eigen-directions). Therefore, movements parallel to eigen-directions, which do not require the covariant/contravariant transformation, could be extremely accurate. Movements in other directions, which require the covariant/contravariant transformation, will yield characteristically curved trajectories (e.g., in oculomotor movements [10]). However, complicating factors are that covariant/contravariant transformation, and therefore the eigen-directions, are dependent upon the relative angles of the limbs. Furthermore, the failure to find main axes at the internal level is not supportive for this approach.

The next step is how to generalize the above theory to the non-isometric case. Fortunately, in handwriting, joint flexions and extensions have relatively small angular amplitudes, so that eigen-directions may be nearly constant. A further step involves the question of how to generalize to multi-joint movements. Much could be learnt on the basic rules of multi-joint movements from the statistical correlations between the movements of separate limbs [20]. However, it does not seem feasible to analyse all joints of the handwriting apparatus, following the accurate procedure used by Gielen and Van Zuylen [6]. Whatever the complexity of the problem, the motor system is apparently able to cope with the complicating factor of controlling several joints, each requiring a multidimensional tensor. In order to keep the higher-order movement representation economical, a tensor of tensors seems to be required.

Does the notion of main axes which differ from the usual horizontal, i.e., base-line, and vertical axes, imply that movements should be analysed in terms of these main axes? In some applications, it may be an advantage to analyse handwriting movements in terms of the mathematical horizontal and vertical axes. The advantages are based on the different roles which these components play in the production of legible handwriting. For example, the main purpose of the horizontal component is the translation from left to right, which prevents the characters from being superimposed. The vertical component actually produces the microstructure of the characters. Indeed, the horizontal and vertical components appear to have different relevance with respect to human recognition of handwriting. Variations in the vertical component show more severe 'visual' distortions in the writing trace, than similar variations in the horizontal component [22]. It seems that whenever the movement aspects prevail, the main axes may be used, and whenever the functional (e.g., communicative, visual) aspects prevail, the mathematical horizontal and vertical axes. For applications such as handwriting simulation, the results show that nonorthogonal coordinate systems [4] are not well supported.

Main axes are, in general, not the movement directions that occur most frequently in normal handwriting. The frequency distribution of movement directions depends rather on the habits in alphabetic writing and on the possibilities of the writing tool. For instance, in the usual style of connected handwriting, straight downward strokes are very frequent [8]. In free stroke performance pushing the pen upward to the left occurs infrequently [21], even though it is a relatively accurate movement. This is probably because the traditional writing tool could get caught in, or damage the writing surface.

Factors Determining Movement Time

The results of this study imply another factor influencing the time needed to execute a segment of a handwriting trajectory. The factors are not only overall size (macro context), relative size (meso context), shape (micro context) of the stroke, presence of translation, presence of other harmonic components [19], and repetition of letters [16] but also orientation of a stroke. The fact that so many parameters affect movement duration does not support the notion that it is a parameter at the highest level of the motor system [5], [17] An interesting observation is that stroke duration gradually increases from a minimum for wrist-joint movements, up to a maximum for finger-joint movements In other words, it is surprising that the finger-joint component does not appear to form a limiting factor for the oscillation speed. Finally, the results show that the maximum oscillation speed of each main axis is very close to the normal handwriting-movement frequency (5 Hz, corresponding to 100 ms per stroke). Thus the temporal planning of movements must take into account the limitations of the handwriting apparatus. The fact that the slow finger-joint movements do not seem to form a limiting factor, and that the timing of those highly different finger-joint and wrist-joint systems show no systematical differences in the resulting movement, demonstrates that the handwriting apparatus is able to solve all these complex problems in an optimal, flexible way.

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Discussion

No Support for Axes at the Central Level

The main result of the reported research is that movement properties of the handwriting apparatus can be described in terms of two main axes: one corresponding to the wrist joint and one to the finger joints. However, neither systematic timing differences could be found between these movement axes, nor a strict limiting-factor effect due to the slowest of these axes. This supports a model picturing movements as coded in terms of an external frame of reference at the central level (e.g., Morasso, 1981). This may explain why writing at different locations of the page with widely varying hand orientations can be performed without the corresponding large changes of orientation or slant, (Maarse et al., 1986), and why voluntary manipulation of slant and orientation of handwriting is easy to perform (Pick & Teulings, 1983).

CHAPTER 5. RECORDING AND PROCESSING

The preceding chapters dealt with research into the microstructure of handwriting movements. For that purpose, various types of data could, in principle, be recorded. One could record physiological signals such as electromyograms of various muscles involved (e.g., Vredenbregt & Koster, 1971), or one could record the complete movement of all limbs and fingers in three-dimensional space (e.g., Van Emmerik & Newell, 1988). A new development is the recording of the pen orientation (Maarse et al., 1988). These data would be eminently suited to answering detailed questions about the biomechanics of handwriting movement. In the present series of investigations, however, only the movements of the pen tip and the axial pen pressure were recorded. These data constitute the intended movement in its most reduced form. It seemed suitable to exploit the information contained in the movement of the pen tip, as this reflects the ultimate goal of the handwriting movements in the most direct sense. The present, final chapter deals with the technical considerations that are relevant for the reliable reconstruction and analysis of the continuous writing movements when using a commercial digitizer. In order to do this properly, basic knowledge concerning the frequency spectrum of handwriting movements is required.

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DIGITAL RECORDING AND PROCESSING OF HANDWRITING MOVEMENTS

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Methods of recording and processing handwriting movements by means of a computer controlled digitizer are discussed It is concluded that the presence of measurement 'noise in the sampled movements makes it necessary to choose high sampling frequencies in combination with low-pass digital filters especially if time derivatives have to be estimated However increasing the sampling frequency beyond some critical value does not improve the signal-to-quantization noise ratio unless the raw samples are preprocessed by summing groups of samples In order to correct for occasional nonsimultaneous sampling of the x and y-coordinates a second type of preprocessing is required (linear interpolation) Subsequently it is shown that low-pass filtering and differentiation can be carried out in the frequency domain using FFT if suitable extrapolation time functions and filter characteristics are chosen Finally various automatic procedures for the division of movement patterns into meaningful segments and a procedure for estimating the accuracy of the digitizer are proposed

Introduction

Research in the area of fine motor skills such as handwriting, for which various kinds of movement recording devices are employed, has a long history (Bauer et al 1969; Crawshaw and Ottaway 1977; Denier van der Gon and Thuring 1965, Drever 1915, Fradis and Gheorghita-Sevastopol 1969, Grunewald and Koster 1960, Katz 1948, 1951; McAllister 1900, Michel 1971, Prablanc and Jeannerod 1973, Scripture 1895; Steinwachs and Barmeyer 1952) During the last 10 years, digital computers and a variety of input/output devices have become available

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for movement research. They allow the accurate recording and automatic processing of movement patterns. It is now feasible to carry out large-scale handwriting experiments designed for as many as 10,000 trials while each trial, comprising hundreds of penposition coordinate pairs, may yield tens of data items like durations and top speeds of individual up or down strokes (e.g., Teulings et al. 1983; Stelmach and Teulings 1983). It is also feasible to estimate parameters based on as many as 10,000 seconds of continuous handwriting (Maarse and Thomassen 1983). Furthermore, computer-assisted training, where the subject receives feedback of a specific movement characteristic, can now be realized (e.g., Søvik and Teulings 1983; Maarse et al. in preparation). The present article surveys some of the digital recording and processing techniques employed in the authors' laboratory.

For the investigation of handwriting movements, a digital computer system is required which is equipped with a device for digitizing positions of the tip of a stylus and with a graphical display, while a large data-storage medium and floating-point hardware are desirable. Handwriting movements can, for instance, be recorded by means of a digitizer which has a stylus with normal appearance. Digitizers are designed to transmit to a digital computer single pairs of horizontal and vertical coordinates of the current position specified by a cross-hair cursor or by the tip of a stylus. If the digitizer is programmed to sample the coordinates of the stylus tip at a sufficiently high rate, all static and dynamic characteristics of the movements by the stylus tip can, in principle, be obtained by appropriate processing procedures.

Sampling and preprocessing

The first step is to acquire sufficiently accurate position information about the handwriting movement so that the digitized movement can be processed easily in order to obtain the desired static and dynamic characteristics. The standard procedure of recording continuous handwriting movements is to sample simultaneously the x- and y-coordinates of the pen tip at a fixed sampling frequency f. If the pen is lifted during the recording period and if, in that case, the digitizer stops generating reliable samples, the correct number of samples should be inserted or replaced so that continuity of the sequences of x and y samples is assured. The inevitable noise and disturbances in the position data will demand complicated preprocessing procedures. For reasons of exposition the hypothetical case 'that there is no noise at all' will first be discussed.

Sampling frequency without noise

It is assumed that handwriting possesses a finite bandwidth, i.e., the frequency spectrum of handwriting movements does not exceed a maximum frequency W. This is reasonable if it is realized that a finite number of motorneurons and muscle fibres is involved, having finite refractory periods and that inertial and frictional forces attenuate the remaining high frequencies. Although the time-varying coordinates are sampled in a discrete series of (equidistant) time moments, it is still possible to reconstruct, in the noiseless case, the continuous time function of the coordinates, provided that the sampling frequency f is chosen to be at least twice the highest relevant frequency W (the Shannon sampling theorem; Whittaker 1915; Shannon 1949; for a review, see Jerri 1977). In that case, the time function of one coordinate at an arbitrary time t (e.g., $x(t)$) can be reconstructed by a weighted sum of neighbouring sampled coordinates:

$$x(t) = \sum_{k=-\infty}^{+\infty} x(k/f)\,\frac{\sin(\pi(ft-k))}{\pi(ft-k)} \tag{1}$$

Taking samples at discrete moments of time does not reduce the amount of information on the original time function in the noiseless case. This reconstruction procedure will not work properly if the sampled coordinates are disturbed by noise. There are at least two sources of noise influencing the digitized coordinates, these two sources will be integrated in the following model.

Model integrating white noise and quantization noise

The tip of the stylus may occupy arbitrary positions on the continuous surface of the digitizer. Via some electro-magnetic or acoustic field, subject to all kinds of disturbances inherent to analog signals, the analog position is converted to digital numbers. Subsequently, this analog-to-digital conversion introduces rounding-off errors. In the present model of 'coordinate noise' it is assumed that the first type of disturbance can be characterized as *white noise* (i.e., with zero mean, some specific standard deviation, and uncorrelated over time). In reality, artifacts (i.e., outliers scores amongst the sequence of samples) may also occur, but they should first be removed by deterministic methods Subsequently, the conversion into digital values brings about rounding-off errors due to the finite spatial quantization-step size of the digitizer (which is usually between 0 01 mm and 0.3 mm); this will be called *quantization noise*. Quantization noise may have properties which differ from those of white noise. Therefore the model for the case in which white noise is dominant (viz., when the quantization noise amplitude i.e., half the quantization-step size is negligible in comparison to the white-noise amplitude) will first be worked out

It may be anticipated here that in unbiased estimates of the x- and y-time functions from noisy data only those noise-frequency components that are not confounded with the signal-frequency components will be attenuated by means of an adequate low-pass filter. These estimated time functions show zero crossings or dips and their specific time moments are directly or indirectly used to test hypotheses in motor research In order to avoid any bias in the final data it is indeed necessary to analyse unbiased estimates of the time functions

Sampling frequency in the presence of white noise

It can be shown that in the presence of white noise, and especially if it is wished to estimate the zeroth, first and second time-derivatives (i e., original position, velocity and acceleration as a function of time, respectively), a much higher sampling frequency, which enables noise reduction, has to be chosen. In Appendix A Lanshammar's (1982) inequality (relation A1) - which expresses the variance of the estimated time derivative as a function of the variance of the raw sampled data, the sampling frequency f and the bandwidth W of the writing movements is evaluated. This evaluation leads to the result that the required *oversampling ratio* (i.e., the factor that the actual sampling frequency f should be higher than its Shannonian lower bound $2W$) satisfies

$$\frac{f}{2W} > \frac{1}{2k+1}\left(\frac{W}{f_0}\right)^{2k}\frac{SNR_k}{SNR} \qquad (2)$$

where f_0 is a fundamental frequency in handwriting movements, W is the highest "significant" frequency, SNR is the signal-to-noise ratio of the raw sampled signal, and SNR_k is the desired residual signal-to-noise ratio of the unbiased estimate (after noise reduction) of the k th time derivative ($k = 0, 1, 2, \ldots$) This inequality shows indeed that a decrease in the signal-to-noise ratio SNR of the raw signal can be compensated by a proportional increase of the sampling frequency f. But the required sampling frequency would grow very rapidly with W if it is wished to estimate, for example, the second time dervative, as the following example demonstrates. Handwriting contains up and down strokes that are performed in approximately 100 msec, so f_0 is of the order of 5 Hz. If only frequencies up to 10 Hz are significant and if SNR_2 (i e., the signal-to-noise ratio of the second time derivative) does not need to be better than SNR, an oversampling ratio of 3.2, corresponding to a sampling frequency of 64 Hz is already needed. If frequencies up to 20 Hz are still significant the above relation would have yielded an oversampling ratio of 51.2, which corresponds to a sampling frequency of 2048 Hz. A sharp estimate of the bandwidth W is therefore important, since, in general, the hardware of a digitizer puts limits to the sampling frequency and the accuracy.

Although relation 2 suggests that the signal-to-noise ratio of the k th derivative estimate SNR_k may attain arbitrary higher values by simply increasing the sampling frequency f there is a reason to suppose that ultra-high sampling frequencies are less appropriate. In the derivation of the original relation A1, Lanshammar (1982) assumed additive white noise, but in the case of additive quantization noise, the noise spectrum does not need to be flat over the entire frequency range. To elucidate this, a model will be presented for the case that quantization noise is dominant, for instance, if the quantization-noise amplitude (i.e., the half quantization-step size) is much larger than the white noise amplitude.

Sampling frequency in the presence of quantization noise

In Appendix B it is argued that the amplitude spectrum of the quantization noise is flat, like the white-noise spectrum, up to a critical frequency (equal to the maximal pen speed divided by the quantization-step size). Above this critical frequency, the noise spectrum varies approximately inversely with frequency. This implies that the total bandwidth is confined to about this critical frequency, so that a sampling frequency of twice this critical frequency is sufficiently high to describe the signal including the noise (Shannon sampling theorem) If, for instance, during normal handwriting the maximal pen speed is 10 cm/sec (e g., 6-mm loops written within 200 msec) and the quantization-step size is 0.3 mm, the critical frequency becomes 333 Hz It should be realized that the critical frequency for low-speed strokes is much lower. In this case, the sampling frequency does not need to be chosen much higher than 666 Hz.

Imagine the case that, for example, the x-coordinate of a near-vertical low-speed stroke is rounded off in the same direction to the closest integer value for a larger number of subsequent samples. This problem does not occur if the digitizer randomizes the integer output between the two closest integer device coordinates (with appropriate weights), thus introducing high-frequency components. It should be noted that white noise with an amplitude of the order of the quantization-step size will bring about this randomization. Since the quantization-noise variance is always $q^2/12$, where q is the quantization-step size (e.g., Oppenheim and Schafer 1975), less low-frequency noise contributions would be within the signal bandwidth in the latter case. But, in most analog-to-digital converters this kind of randomized output is suppressed by means of hysteresis in the conversion circuits.

Another solution would be to simulate a smaller quantization-step size using a method which is slightly different from the above mentioned randomization between the two closest device coordinates, and which can be implemented in software.

Simulating a small quantization-step size

If the digitizer allows a much higher sampling frequency than the above estimated critical sampling frequency, a high sampling frequency $f' = Nf$ can be used in yet another way, namely by just summing adjacent groups of N samples (without division by N). This can be regarded as a type of preprocessing – as convolution with a rectangular smooth window, with a duration equal to $1/f$ (which attenuates frequencies between f and f'), and as the subsequent decimation of the number of samples to f per second. It may be noted that the apparent quantization-step size is $1/N$ times the hardware quantization-step size. The resulting sample represents the mean position (multiplied by N) during one (effective) sampling period ($T = 1/f$), delayed by half the period. This procedure works as long as the digitizer internally refreshes the current pen position at a high rate and when at least one quantization step is transferred per sampling interval.

As argued above, the sampling frequency does not need to be chosen much higher than 666 Hz in the present example even if a small quantization step is simulated by actually summing N samples within each sampling interval of 1/666 sec. The summing acts as a primitive prefiltering and decimation of the number of samples to be stored or to be processed during the analysis stage. A 666-Hz sampling frequency may produce still too many samples to allow convenient processing, and therefore a decision might be taken to lower the sampling frequency while increasing the number of samples N that are summed within each sampling interval. If the sampling frequency is chosen too low, however, this summing procedure may cause some bias. Namely, if a curved writing trace is digitzed and N samples during one sampling interval ($T = 1/f$) are summed, then the resulting sample will be off the curved writing trace. In Appendix C it is shown that the maximal spatial departure (d) of the mean position from a sampled circular movement trace with radius R which is drawn in time T_c may be set equal to $d = (R/6)(\pi/fT_c)^2$. By demanding that the spatial departure d should be less than some required error (e.g., half of the digitizer's quantization-step size: 0.15 mm) the lowest sampling frequency f that is still appropriate can be estimated. The maximal ratio of R/T_c^2 (obtained in circles with radii $R = 20$ mm, which can be drawn in about $T_c = 280$ msec), yields the result that f should be higher than 50 Hz. Sampling frequencies between 100 and 200 Hz are therefore used which seem to form a reasonable compromise between signal-to-noise ratio on the one hand and total amount of data and computing load on the other.

Sampling frequency in the presence of both white noise and quantization noise

In general, both noise types are present in the sampled coordinates. White noise and quantization-noise are uncorrelated, such that their individual noise variances and power spectra must be added to yield the total noise variance and the total power spectrum. This has been concluded from Oppenheim and Schafer (1975) who found evidence, by means of simulations using a large range of quantization-step sizes, that the input to the quantizer and the quantization noise are uncorrelated.

The same must hold if white noise or white noise superimposed on some time-varying signal, e.g. the position-time curve, are quantized. Conclusions based on each type of noise also hold in the present case.

In Appendix D a standard procedure is proposed to estimate the total digitizer noise variance per coordinate. This total noise-variance estimate is based on movement patterns (with limited degrees of freedom, however), in contrast to Lanshammar's (1982) estimate, which is based on stationary-position noise, which would be zero in the present case, since the quantization-step size is relatively large. The digitizer used to acquire the spectra (Vector General Data Tablet, DT-1) yielded a white-noise standard deviation of approximately 0.1 mm and an (effective) quantization noise standard deviation of 0.09 mm per coordinate. The total standard deviation per coordinate is 0.13 mm and combined for both coordinates it is $\sqrt{2}$ times larger or 0.18 mm.

The procedure for estimating the accuracy of the digitizer assumes that all types of systematic errors are negligible or have been eliminated. One systematic error comes from the nonlinearity across the digitizer surface which can be corrected easily. A less trivial systematic error is introduced by the asynchrony of x- and y-samples.

Anisochronous or nonsimultaneous x- and y-samples

Ideally, x- and y-coordinates are sampled at equal *and* equidistant moments of time. But, the hardware and the software of some digitizers do not allow the sampling of coordinate pairs at well-defined instants of time. Delays in the sampling of the coordinate pairs seem to be of minor significance as long as they remain relatively constant or change slowly. If the times of sampling the coordinate pairs are known, the desired samples can be estimated by fitting the data by spline functions (e.g., Soudan and Dierckx 1979) or by sine functions (yielding the Fourier coefficients directly, see for example Piessens 1971).

A severe distortion may be expected if the x- and y-coordinates of one pair are not sampled simultaneously but if there is a delay in, for example, the y sample relative to the x sample which is of the order of the sampling interval. This occurs when the digitizer is operating with a relatively slow position scan or when it scans the x- and y-axes alternately. The extent to which x and y samples are not taken simultaneously can be easily checked by sampling fast pen movements along a ruler in two opposite, diagonal directions When the sampled x- and y-pairs are plotted, the up and down movements will appear as oppositely curved lines instead of straight lines If the delay is known and is constant, the problem can be solved almost exactly by multiplying the y-contribution to the Fourier spectrum with the corresponding complex phase factor If, on the other hand, the delays vary, x and y samples should be estimated by means of interpolation functions The interpolation functions should be based on nonequidistant samples, but in local interpolations the delays may again be supposed constant such that sinc functions, viz , $\sin(\pi(ft - k))/\pi(ft - k)$, can be used as in eq (1) If the oversampling ratio is high enough, however, linear interpolation between successive samples (i e , a triangular interpolation function) becomes attractive because of its simplicity if the delay of coordinate $y(t)$, relative to the sampling interval T can be expressed as $\alpha = (a + by(t))/T$ (i e , a constant-velocity position scan), then the estimate of the nondelayed coordinate is $\hat{y}(t) = (1 - \alpha)y(t) + \alpha y(t + 1)$

Analysis

In its most strongly reduced form, the dynamic handwriting signal can be regarded as a two-dimensional signal The pen pressure and pen height signals may be omitted since these signals are mostly treated in a separate way Signals in two-dimensional space can also be described in one-dimensional complex space An important tool for analyzing complex signals is the discrete Fourier transform For numerical work, various fast-Fourier transform (FFT) algorithms have been developed (e g , FFTs based on polynomial transforms, Winograd algorithms, Good algorithms or radix-4 algorithms, see Cooley and Dolan 1979) The number of real multiplications to transform N complex data, using an ordinary (radix-2) FFT algorithm is of the order of $\frac{1}{2}N \log_2(N)$, while a Winograd algorithm may reduce net computation time to 60% of the computation time of the radix-2 FFT and an efficiently programmed radix-4 FFT (Morris 1979) even to as little as 40% (cf , Elliott and Rao 1982)

The Fourier transform requires a cyclic signal

The FFT assumes that the signal repeats itself fluently after an algorithm-dependent number of samples In normal handwriting, the beginning and end of the movement pattern may be spatially far apart and the number of samples is generally not appropriate. In order to solve both problems the signal can be appended with an extrapolation function which smoothly connects the beginning and the end of the x- and y-time functions. Alternatively, the linear trend can be removed so that the coordinates of the first and the last sample coincide, and later corrected for this detrending in a way which depends upon the type of operations performed in the frequency domain (Wood 1982). In short handwriting trials, the pen is at rest at the start and at the end of the recording period, so that appending a half-cosine wave can make the signal cyclic in a continuous way. If, on the other hand, the beginning or the end of the sampling period happen to occur during a pen movement, a third-order polynomial may be constructed to meet the requirements. In the latter case, the exact course of the movement outside the sampling period is still uncertain, so that both ends of the processed signal may be unreliable. The extrapolation function cannot be made arbitrarily short since it should not bring about high-frequency components that might be filtered out in subsequent data processing.

Filtering

The FFT applied to the handwriting signal (which has been made cyclic) yields a (complex) frequency spectrum. The inverse FFT would yield the original signal again. But before the inverse FFT is applied the complex spectrum is multiplied by some real low-pass frequency characteristic. This procedure is equivalent to well-known time-domain smoothing procedures which use convolution with a smooth window (apart from the fact that the window width is limited, yielding a finite-impulse response or FIR filter) whose shape equals the inverse Fourier transform of the filter-frequency characteristic.

The ideal low-pass filter gain is 1 (passband) for all low-frequency components which are supposed to be relevant, and 0 (stopband) for all irrelevant high-frequency components. It is possible to realize a sharp transition between passband and stopband, but this way of smoothing would introduce oscillations (Gibbs' phenomenon) at abrupt movement changes, especially in estimates of time derivatives. In Appendix E is shown that an optimal transition band, which introduces only one Gibbs-oscillation phase, consists of a sine that fluently connects the passband and the stopband while the total width of the transition band is 8/3 of the passband. In pilot studies it was found that time-domain smoothing windows (FIR-filters) that are designed with a 8/3 ratio between transition bandwidth and pass bandwidth (Rabiner and Gold 1975) also show relatively few Gibbs' oscillations. The question now arises, which passband frequency should be taken in order to yield unbiased estimates.

Passband frequency

As can be seen from relation 2 the signal-to-noise ratios of estimates of time derivatives fall rapidly when the supposedly highest relevant frequency W increases. Thus it is very important to accurately estimate the highest relevant frequency. It is not trivial to determine this highest relevant frequency, since the power-frequency spectra due to movement and due to the noise cannot be statistically separated in an analogous way as done in the design of a Wiener filter. In particular, an unbiased ensemble average of a specific handwriting pattern cannot be determined because local temporal retardations in replications of a movement pattern result in asynchrony between ensemble members.

In fig. 1 an estimate of the amplitude spectrum of handwriting velocity is depicted. The amplitude spectrum is based on 600 adjacent segments of handwriting from 20 subjects, who were copying a 2.56-minute prose text at relaxed pace. Sampling frequency was 100 Hz. Each 512-sample segment was made cyclic using a half-cosine wave and after multiplying with a Hamming window a 1024-point FFT was applied. Subsequently, the spectral components are multiplied by their frequency in order to amplify the high-frequency part, thus obtaining the spectrum of the movement velocity. The absolute values of the spectra are averaged thus obtaining an estimate of the amplitude spectrum, while reducing effects due to outliers. This procedure resembles the Welch (1967) method except that the amplitude spectrum is estimated instead of the power spectrum. It can be seen that the amplitude spectrum asymptotically approaches a rather flat noise spectrum at about 10 Hz.

Since handwriting movements appear to possess important frequency components at about 5 Hz, it is remarkable that components higher than 10 Hz (i.e., the second and higher harmonics) do not seem to be strongly represented in handwriting (see fig. 1). Obviously, handwriting viewed as a function of time contains less repetitive and bumpy

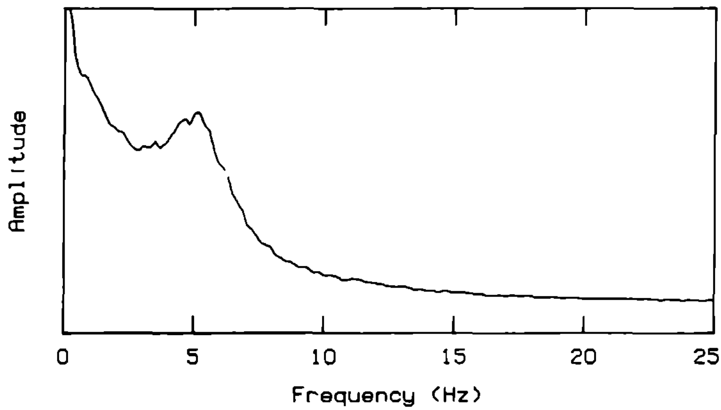

Fig. 1 Average amplitude spectrum of the velocity-time functions (sampling frequency is 100 Hz)

movement patterns than, for example, gait, which has a spectrum showing of the order of 10 harmonics (e.g., Lanshammar 1982; Wood 1982). The absence of higher harmonics in handwriting movements merely suggests that parts of the handwriting signal may be approximated by a phase-modulated signal. It can be shown that with realistic modulation parameters the spectrum would indeed be confined to 10 Hz (see Appendix F).

A low-pass filter having a flat passband of about 10 Hz should therefore be chosen. But, if the first or the second time derivative has to be calculated, lower pass-band frequencies may be necessary in order to obtain a reasonable compromise between signal-to-noise ratio of the estimated time derivative and bias of the estimate due to oversmoothing.

Time derivatives and other functions

A smoothing procedure can be combined with the estimation of time derivatives. In the frequency-domain method, an unbiased estimate of the time derivative can be determined by multiplying the components of the complex spectrum by their corresponding frequency (actually by $j2\pi f$, where $j = \sqrt{-1}$) prior to applying the inverse FFT (e.g., Papoulis 1977).

Besides position, most relevant time functions in motor research are velocity (i.e., the first time derivative), acceleration (i.e., the second time derivative), and the absolute speed. From the filtered x and y velocities the direction of movement can be estimated on a sample-by-sample basis. If continuity is taken into account, this function integrates the angle across which the velocity vector has been rotated from some starting point (the "running angle", cf. Teulings and Thomassen 1979; Thomassen and Teulings 1979). Its time derivative is known as the angular frequency or angular velocity. The angular frequency may also be estimated from the inner product between the normal of the velocity (v) and the acceleration (a) vectors, viz., $(v_x a_y - v_y a_x)/(v_x^2 + v_y^2)$. Finally, the curvature (i.e., the inverse curve radius) is determined by the angular frequency divided by the absolute velocity.

Automatic processing

Most experiments require many handwriting trials to be processed and each handwriting trial yields many segments to be analyzed (e.g., separate strokes). Automatic procedures can carry out this task accurately so that the experimenter merely needs to check whether the segments (indicated by time marks in the displayed patterns) have been determined correctly. In order to divide a handwriting movement pattern into segments two types of time functions can be used: double-phasic (e.g., vertical velocity) and single-phasic time functions (e.g., absolute velocity). Vertical velocity, for instance, allows division into vertical up-strokes and down-strokes. Absolute velocity allows division into more or less ballistic strokes in a rotation-invariant way since the absolute velocity shows dips at instances of high curvature (Lacquaniti et al. 1983). In simple, upright handwriting patterns both velocity functions yield about the same time marks.

Two types of time-mark search procedures can also be discerned. By means of the first type the time moments of extrema of a certain time function (e.g., y-position) can be determined from the zero crossings of its estimated time derivative. These time moments can easily be approximated by linearly interpolating between the two velocity samples surrounding the zero level. A disadvantage may be the necessity of estimating one more time derivative. By means of the second type of time-mark search procedure global extrema of a time function can be determined so it is not necessary to use its time derivative. For example, in the absolute-speed time function the lowest dips correspond to points of high curvature in the writing pattern, and only these dips usually coincide with the beginnings of new strokes, whereas less pronounced dips belong to irrelevant variations in the curvature. Therefore, the search algorithm should locate the sample numbers of all dips first and then select those of the lowest dips. The points in time at which the real minima probably occur can be estimated at a higher resolution than the time discretization interval, by means of interpolation with a second-order polynomial through the lowest sample and its two neighbours. A more exact but slower interpolation method consists of appending a large number of zeros to the high-frequency end of the spectrum prior to performing the inverse Fourier transform (Gold and Rader 1969).

A time-mark search algorithm generally comprises two steps, first a raw search, then an accurate search. Even after smoothing, a small percentage of time marks cannot be determined unambiguously, and a suitable algorithm should also cope with these rare cases. For example, an algorithm to detect zero crossings might be designed as follows: determine the positive and negative top levels of the curve, search forward for an upgoing crossing at intermediate positive level, search backward for the upgoing jump at zero level, jump a number of samples, search forward for a downgoing crossing at intermediate negative level, etc.

Sometimes the experimenter wishes to determine the time marks interactively which is especially needed for the irregular handwriting patterns produced by young subjects. For that purpose a display screen is used on which a set of cursors can be moved quasi-continuously along the curves by turning a knob or by moving the digitizer stylus. When a switch is operated, the current position of the cursors becomes a time mark. This procedure can be speeded up by combining it with an automatic search. If the automatic option is switched on, a second set of cursors is visible at a subsequent time mark, located by the automatic algorithm. A new time mark is computed when the controlled cursor approaches the cursor representing the old location. Now the experimenter may choose whether the manually or the automatically located cursor becomes a time mark. In this way, time marks can be determined interactively and with much ease and accuracy.

Conclusions

Digitized handwriting movements yield a special class of signals since the local handwriting movements are mainly of interest (e.g., strokes may be as short as 1 mm), whereas the spatial positions during one handwriting trial may have a large dynamic range (e.g., line lengths may be as long as 210 mm). Quantization noise may therefore present a severe problem in analyzing individual strokes It has been argued that the relatively raw quantization puts limits on the highest useful sampling frequency, since above a critical frequency (equal to the maximal velocity divided by the quantization-step size) the noise-amplitude spectrum decreases at 6 dB/octave Since it is wished to pay special attention to the small strokes, the critical frequency may be rather low. The signal-to-noise ratio will not improve, according to the prediction of relation 2, by increasing the sampling frequency beyond twice this critical frequency. Lumping adjacent samples, taken at a high frequency, together however, may provide a reasonable means of coping with relatively strong quantization effects

A problem in multidimensional movement recording seldom reported is that the x- and y-coordinate should be sampled simultaneously for those cases where functions have to be estimated that combine x- and y-coordinates (e g., absolute velocity). In specific cases nonsimultaneous samples can easily be corrected by means of linear interpolation.

A standardized procedure is proposed to estimate the accuracy of a digitizer under moving-pen conditions. According to this procedure two straight lines, having different slopes, are sampled. From the variance of the distances between the samples and a fitted straight line the variances per coordinate can be estimated.

A convenient property of the handwriting signal is that it does not contain many harmonics: The most important frequency components are found around 5 Hz, while nearly all components are confined to frequencies below 10 Hz. Minimal-bias estimates from the noisy data can be obtained by applying a lowpass filter with a flat passband of 10 Hz. In order to reduce inevitable Gibbs' oscillations, a sinusoidal transition band is proposed from 10 Hz to 37 Hz

In order to conduct large-scale handwriting experiments, automatic time-mark search procedures are proposed. In most of the recent handwriting analyses in the authors' laboratory the search has been for vertical-velocity zero crossings for finding vertical-position extrema, or for absolute-velocity dips. The movement segments defined in the latter way are similar to ballistic strokes.

Appendix A

Oversampling ratio as a function of signal-to-noise-ratio

Assume a strictly bandwidth-limited sampled signal, with maximum frequency W and sampling interval T, which is disturbed by some additive white noise with standard deviation σ. Lanshammar (1982) has shown that the unbiased estimate of the kth time derivative ($k = 0, 1, 2, \ldots$) still contains a residual noise component (which is not necessarily white) whose standard deviation σ_k satisfies

$$\sigma_k^2 \geqslant \frac{\sigma^2 T (2\pi W)^{2k+1}}{\pi(2k+1)} \tag{A1}$$

The demand that the estimate of the kth time derivative should be unbiased up to W is operationalized by demanding that the estimate has to be exact if the noise has zero standard deviation. Thus all frequency components below W remain untouched while the frequency components higher than W are attenuated. This type of smoothing is still rather conservative as compared to classical Wiener filtering (which minimizes the mean quadratic error; Wiener 1949). A Wiener filter generally causes a bias since frequency components lower than W are attenuated to some extent too.

If only the signal-to-noise ratio of an estimate is relevant, it is important to realize that in time derivatives the high-frequency part of the signal is amplified as well. This can be taken into account by defining the Relative Noise Amplification (Lanshammar 1982). Here, the signal-to-noise ratio of the estimate will be approximated in a way which specifically holds for handwriting signals (e.g., the y-coordinate as a function of time). Parts of the estimated signal may be approximated by some sine wave with specific amplitude A and frequency f_0. Thus the signal-to-noise ratio SNR may be set to:

$$SNR = \frac{A^2}{2\sigma^2} \tag{A2}$$

where σ is the standard deviation of the additive white noise contained in the raw sampled signal. The kth derivative of the approximation yields an amplitude:

$$A_k = A(2\pi f_0)^k \tag{A3}$$

and a new standard deviation of its residual noise component which is set equal to σ_k. Thus the signal-to-noise ratio SNR_k of the estimate of the kth time derivative becomes:

$$SNR_k = \frac{A^2 (2\pi f_0)^{2k}}{2\sigma_k^2} \tag{A4}$$

Substitution of eqs (A3) and (A4) into relation (A1) yields, after some rearranging

$$\frac{f}{2W} > \frac{1}{2k+1}\left(\frac{W}{f_0}\right)^{2k}\frac{SNR_k}{SNR} \tag{A5}$$

The left hand term of relation (A5) may be referred to as the *oversampling ratio* which indicates the number of times that the sampling frequency f should be higher than the minimum sampling frequency (equal to $2W$) in order to allow reconstruction of the original signal, in the noiseless case (Shannon sampling theorem) The need for a higher sampling frequency arises therefore from the need to improve the concrete signal-to-noise ratio of the raw, sampled signal (SNR) to the required signal-to-noise ratio of the estimate of the k th time derivative (SNR_k)

It should be noted that the inequality sign in relation (A5) is not as strict as the one in relation A1 because of the approximation of parts of the handwriting movements by sine waves For a large record of handwriting the sine waves may be characterized by one sine wave with a frequency corresponding to the highest-frequency peak in the spectrum The amplitude A does not appear in relation (A5) Its value occurs in the SNR estimated according to eq (A2)

Appendix B

Quantization-noise spectrum

In the following heuristic derivation the amplitude spectrum of the quantization noise in discrete time series will be estimated In the main, the input to the quantizer is assumed to be a stationary, random process having a specific amplitude probability density (Kellogg 1967, Kosyakin 1961) The present derivation deals with a quantization problem specific to the digitizing of handwriting movements Local movements are of most interest in handwriting, but they are distorted by the quantization noise, while the large left to right movements determine the dynamic range of the quantizer

Imagine that the stylus is travelling on the digitizer along one coordinate axis at constant (positive) velocity v For convenience the transfer rate V of quantization levels within one sampling interval will be defined as T, viz ,

$$V = vT/q \tag{B1}$$

where q is the distance between the quantization levels (i e , the quantization-step size) So the real coordinate value at the time of sample i ($i = 0, 1, 2,$) is $x(i) = Vi + x_0$, where x_0 is the real pen coordinate at sample $i = 0$ But, when the coordinate is sampled by the digitizer, its value will be assigned to some integer device coordinate by a truncation or rounding procedure It will arbitrarily be assumed that the real coordinate $x(i)$ is rounded to its nearest integer device coordinate $Q[x(i)]$ Hence, the quantization-noise error will be defined as

$$n(t) = Q[x(t)] - x(t) \tag{B2}$$

For convenience $e(V)$ will be defined as the difference between the transfer rate V and its closest integer value $Q[V]$

$$e(V) = Q[V] - V \tag{B3}$$

Then $n(t)$ as a function of t will have a sawtooth-like shape in general (see fig 2) with a fundamental frequency given by

$$f_0 = e(V)/T \tag{B4}$$

(If $e(V)$ is about 1/2 $n(t)$ will approach a triangular shape) Thus the fundamental frequency f_0 varies as a function of transfer rate V according to a repetitive triangular pattern with zeros at integer values of V and peaks halfway between integer values The largest value of the fundamental frequency is $1/(2T)$ which is equal to half the sampling frequency

What is the appearance of the quantization-noise spectrum if the transfer rate V of the stylus along one digitizer axis varies from segment to segment (segments may be as small as a few sampling intervals)? Because of the linearity of the Fourier transform it can be stated that the spectrum of the weighted sum of segments equals the weighted sum of the spectra of these segments The weights may be retrieved from the transfer-rate probability density function $g(V)$ of V

First assume that $g(V)$ is a homogeneous probability density function between $V = 0$ and $V_{max} > 1/2$ In this case all fundamental frequencies from $f_0 = 0$ to $f_0 = 1/(2T)$ and all their harmonics occur with equal probability Harmonics higher than half the sampling frequency (i e $1/(2T)$) do not cause frequency aliasing (cf Oppenheim and Schafer 1975) but are simply absent because they are not needed to describe the sawtooths or the triangles Therefore the quantization noise spectrum is flat under the above assumed probability density function $g(V)$ This convenient and

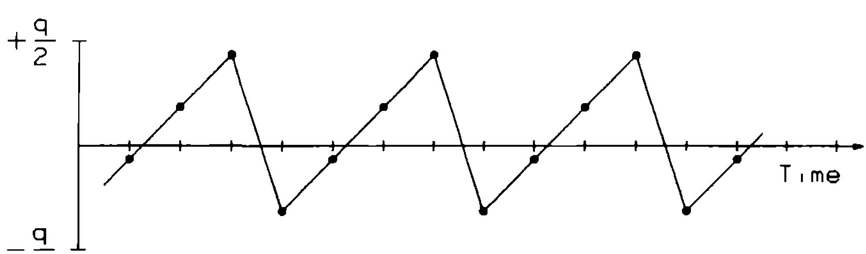

Fig 2 The quantization error $n(t)$ in constant velocity movements along a device axis is approximately a sawtooth ($e(V) = 0.25$ in the present sample)

commonly assumed result has been supported by simulations (e g Kosvakin 1961 Oppenheim and Schafer 1975 Widrow 1956)

If on the other hand $V_{max} < 1/2$ then the spectrum will be white only up to the highest fundamental frequency

$$f_{crit} = \frac{V_{max}}{T} = \frac{v_{max}}{q} \tag{B5}$$

where v_{max} is the maximal pen speed Above this highest fundamental frequency the spectrum will behave like the sum of the tails of the spectra of sawtooth-like patterns The amplitude spectrum of a (stationary) sawtooth has components at frequencies $F = f_0$ $2f_0$ $3f_0$ The corresponding relative amplitudes are $qf_0/(\pi F)$ It may be noted that if V_{max} is close to 1/2 also triangular patterns occur The spectrum of a triangle decays more rapidly with frequency but this may be neglected if $V_{max} \ll 1/2$ Thus the amplitude spectrum of the quantization noise as a function of frequency F is given by

$$\frac{q}{\pi FT} \int_{-\infty}^{+\infty} e(V) g(V) dV \tag{B6}$$

Therefore beyond the critical frequency f_{crit} the noise spectrum varies inversely with frequency

In pilot studies was found that increasing the quantization-step size results in an amplitude spectrum which varies indeed with approximately the inverse frequency (i e -6 dB/octave) This result is in agreement with results by Dessimoz (1980) and marginally with results from simulations by Oppenheim and Schafer (1975) Finally, Bennett (1948) presents power spectra of quantized and band-limited noise which decrease with 6 dB/octave above frequencies of the order of the critical frequency

Appendix C

Bias due to the summing of samples

Suppose a circular movement trajectory (constant speed duration T_c and radius R) is sampled on a digitizer during interval T The average over all samples will not represent a point on the circular trajectory Centering the problem around the y axis we can substitute for the circular movement $y(\alpha) = R\cos(\alpha)$ while α is running from $-\varphi$ to $+\varphi$ and $\varphi = \pi T/T_c$ The average y-coordinate ym can be approximated by

$$\begin{aligned} y &= \frac{1}{2\varphi} \int_{-\varphi}^{+\varphi} R\cos(\alpha)\, d\alpha \\ &= \frac{R}{\varphi} \sin(\varphi) \\ &\simeq R\left(1 - \frac{\varphi^2}{6}\right) \end{aligned} \tag{C1}$$

So the average y-coordinate shows a bias $d = \bar{y} - R$ which equals about

$$d = -\frac{R}{6}\left(\frac{\pi T}{T_c}\right)^2 \tag{C2}$$

Appendix D

Estimation of the accuracy of the digitizer

The accuracy of the digitizer is limited by (a) nonlinearity of the digitizer, (b) the nonsimultaneous sampling of x- and y-coordinates, (c) the effective size of the quantization step, and (d) the white-noise amplitude. The first two accuracy-limiting factors can be identified, and largely eliminated. The effective quantization-step size q produces a variance of $q^2/12$. Only the white-noise variance remains to be determined empirically. The total noise variance consists of the sum of both noise variances since it has been demonstrated from simulations that both variance sources may be assumed to be independent (Oppenheim and Schafer 1975).

The total noise variance can be (over)estimated by means of the following procedure. Sample a few times a straight line drawn at fluent speed along an appropriate and accurate ruler (in each of two different slopes). The slope (i.e., the angle φ with the positive x-axis), the length (l) of the line, and the number (N) of samples are chosen such that all x or y samples are at least one quantization step apart. Then x and y samples may be supposed to be uncorrelated over time, and to have noise variances of σ_x^2 and σ_y^2, respectively. Appropriate values are, in general, $\tan(\varphi) = 3.3$ and 0.33, $l = 10$ cm and $N = 50$. The underlying straight line can be estimated with sufficient accuracy as the line with the least-mean-squared distance $\sigma^2(\varphi)$ to the samples. This line depends upon σ_x, σ_y, and φ as

$$\sigma(\varphi)^2 = \sin(\varphi)^2\sigma_x^2 + \cos(\varphi)^2\sigma_y^2 \tag{D1}$$

By choosing the lowest $\sigma(\varphi)$ at two different slopes one can estimate σ_x^2 and σ_y^2 by solving the two corresponding equations. Furthermore, the white-noise variance of the x-coordinate, for instance, can be estimated as $\sigma_x^2 - q^2/12$ and similarly the variance of the y-coordinate. The combined "planar" accuracy (σ_r) of the digitizer can be defined as

$$\sigma_r = \sqrt{\sigma_x^2 + \sigma_y^2} \tag{D2}$$

If the construction of the digitizer warrants the assumption that σ_x equals σ_y, it is not necessary to solve σ_x and σ_y by varying φ, but it can immediately be concluded that $\sigma_x = \sigma_y = \sigma(\varphi)$ and that $\sigma_r = \sqrt{2}\,\sigma(\varphi)$.

Appendix E

Optimal transition bandwidth for a low-pass filter with a flat passband

If a time signal is smoothed with a sharp cut-off frequency, oscillations (known as the Gibbs' phenomenon) occur at sharp slope changes in the signal. The origin of the Gibbs' phenomenon can easily be understood if it is realized that this type of smoothing (i.e., multiplying in the frequency domain by a rectangular frequency window which is 1 between cut-off frequencies f_c and $-f_c$ and 0 elsewhere) is equivalent to convolution of the time-domain signal with a smooth window. This smooth window equals the inverse Fourier transform of the rectangle, which is a sinc-shaped time function ($\sin(2\pi f_c t)/(2\pi f_c t)$) with sidelobe peaks at the approximate times $t = 0.75/f_c, 1.25/f_c, 1.75/f_c, \ldots$, with relative top values of -0.13, $+0.09$, -0.07, $+0.06$, ... Each of the sidelobes, but especially the negatvie ones, may cause one Gibbs-oscillation phase. Because of their high frequency (f_c) the Gibbs' phenomenon forms a potential problem for estimates of higher time derivatives, as the price for a long and ripple-free passband, a sharp transition band, and an ideal stopband.

However, choosing a filter characteristic with an appropriate transition band will greatly reduce the number and the amplitudes of these undesirable oscillations. In order to derive optimal transition bandwidths, a fluent sinusoidal transition band whose width is set equal to $2f_t$ will be chosen. Such a frequency characteristic can also be regarded as the convolution of the rectangular

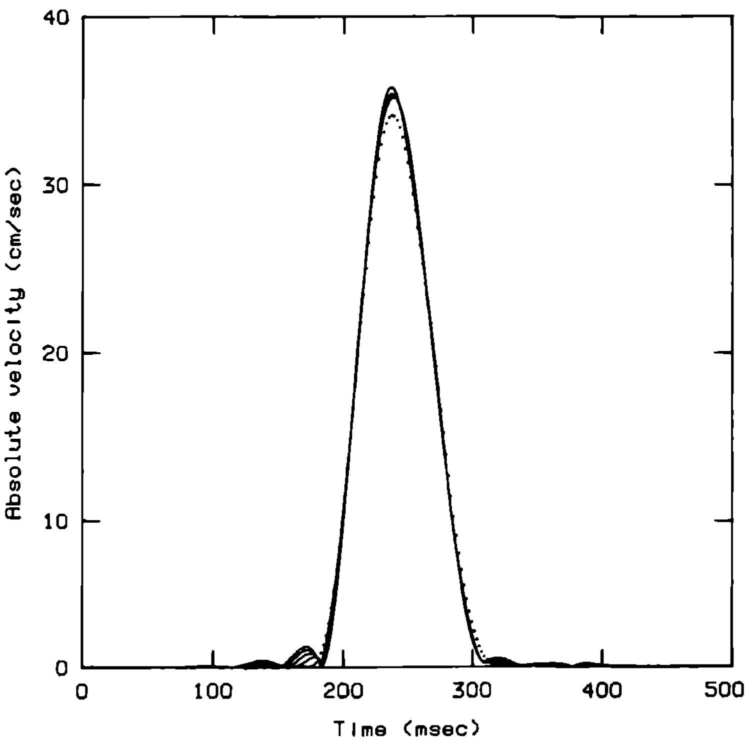

Fig 3

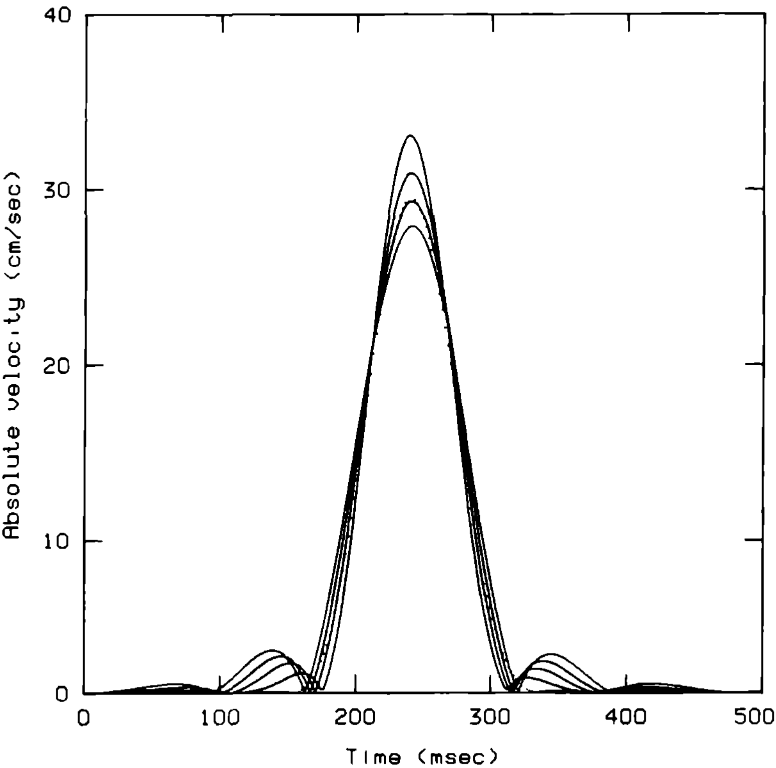

Fig 3 The smoothed absolute velocity time function of a 2.3-cm fast down stroke using pass-bandwidths of 10 Hz (first panel) and 5 Hz (second panel) and various transition bandwidths corresponding to $f_t = f_c/1$ $f_c/1.25$ $f_c/1.75$ $f_c/2.25$ and $f_c/2.75$ (The narrower the transition band the higher the first oscillation phase It should be noted that the transition bandwidth is $2f_t$ and that f_c equals the pass-bandwidth plus f_t The dotted curves represent the special case that $f_t = f_c$ in which case there is actually no passband their transition bandwidths are chosen 50 Hz and 25 Hz respectively The sampling frequency is 500 Hz)

frequency characteristic with a Hanning-shaped or Tukey-shaped window (which consists of a raised sine between the frequencies f_t and $-f_t$) The inverse Fourier transform of this window yields zeros at the times $1/f_t$, $1.5/f_t$, $2/f_t$, ... while the top values of the sidelobes between them decrease rapidly with their order -0.03 $+0.01$ -0.004 $+0.002$ ... If it is again realized that this new frequency domain characteristic corresponds in the time domain with the product of both inverse Fourier transforms optimal transition bands are obtained by matching both transforms such that as many negative sidelobes of the sinc function are attenuated as is possible This can be done by choosing $f_t = f_c/0.75$ $f_c/1.75$ $f_c/2.75$. The first choice (introducing no Gibbs oscillations) must be rejected because it does not result in a flat passband at all The second choice forms the optimal transition band with only one Gibbs' oscillation period Decreasing the transition bandwidth to $f_t = f_c/2.25$ would result in two Gibbs-oscillation periods while increasing f_t to

$f_c/1.25$ would not result in zero periods but only in a decrease of the oscillation amplitude (see fig. 3). Since the aim is to choose a flat passband with the shortest possible transition band at the minimal number of Gibbs' oscillation periods, a low-pass frequency characteristic should be chosen such that the transition band consists of a fluent sine wave having a width of 1.75 times the equivalent cut-off frequency or 8/3 times the pass bandwidth.

Appendix F

Spectrum of a phase-modulated signal

Let parts of the handwriting-position signals be approximated by a phase-modulated signal

$$\sin(2\pi f_0 t + m \sin(2\pi\mu t)) \tag{F1}$$

where f_0 is the fundamental frequency of the movements (5 Hz), m the phase-modulation index and μ the frequency by which successive periods are varied. Subsequent strokes can be varied independently so μ must be of the order of 5 Hz. Stroke durations in handwriting appear to vary from 70 to 140 msec, so the frequency shift ($2df$) is about 3.5 to 7 Hz. m can be estimated by the relation $m = df/\mu = 0.7$, thus $m < 1$. The amplitude spectrum of such a modulated signal contains components at $f_0, f_0 + \mu, f_0 + 2\mu, \ldots$ with amplitude specified by the Bessel functions $J_0(m), J_1(m), J_{-1}(m), J_2(m), J_{-2}(m)$ etc. If $m < 1$ the second- and higher-order functions are negligible. According to this approach the handwriting spectrum is confined to 10 Hz.

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Discussion

Strokes are Independent

An interesting result of the previous study is that the frequency spectrum of handwriting velocity has a peak around 5 Hz and drops to noise level at about 10 Hz. Apparently, most of the energy of the handwriting movement is found within the frequency band between zero and 5 Hz. Therefore, details of the velocity-versus-time curves, and indirectly of the stroke shapes, correspond to components of the higher-frequency part. Consequently, if handwriting is low-pass filtered with a cut-off frequency of 5 Hz, the smallest relevant characteristics tend to disappear (Teulings & Thomassen, 1979). Another consequence of the effective bandwidth of 5 Hz is that the samples of X and Y position taken every 100 ms are independent (Shannon's theorem). It is probably not accidental that the average stroke duration is of the same order of magnitude. This implies that strokes may be independent movement entities. In other words, in normal handwriting, strokes cannot be predicted reliably from previous strokes (except its alternating movement direction). This illustrates that the handwriting motor system is completely using the information-transmission capacity of the peripheral motor system, within its limited frequency bandwidth.

This brings us to the relevant question of how many parameters are required to reconstruct handwriting with sufficient accuracy. This question is of interest because it would allow us to verify whether the information assumed in motor memory is complete. In Chapter 2, we supposed that the topological structure, the stroking sequence and the relative stroke sizes of the handwriting patterns are stored. These three information sources combined yield that the movement information can be visualized as an ordered sequence of positions in the two-dimensional writing plane. Let us compare this picture with three of the existing handwriting-generation models (e.g., Dooijes, 1984; Hollerbach, 1981; Maarse, 1987; Morasso et al., 1983; Schomaker et al., 1988, Vredenbregt & Koster, 1971).

Hollerbach's model has been referred to frequently, probably because it uses a *mass-spring model*, which describes some properties of the motor system appropriately (e.g., Bizzi et al., 1976; Chapter 2). According to this model, handwriting can be generated by oscillations in four springs. The springs are characterized by four spring constants, four virtual fixation points, two (equal) spring frequencies, two oscillation amplitudes, and one phase difference. An interesting feature of this model is that sequences of similar strokes can be generated by a single setting of these parameters, thereby using on average only few parameters per stroke. However, a less favorable feature is that several parameters have to be changed simultaneously prior to each different stroke. This is likely to occur in most of the strokes, as argued previously. The latter feature indicates that this model contains probably too many, or confounded, parameters. It should therefore be feasible to generate handwriting using fewer parameters per stroke.

In Maarse (1987), various models for generating handwriting have been compared. Satisfactory models are based upon time moments of relatively extreme X and Y positions, and upon their distances in X and Y direction, respectively. X and Y extremes occur once to twice every 100-ms stroke. In oval character shapes, they will be close to the velocity minima, which form the stroke endpoints. However, these models only seem very parsimonious, because they do not explain the origin of the moments the X and Y extremes occur. These moments are adopted from existing writing patterns.

Schomaker's et al. (1988) model presents an attempt to include the generation of the moments of X and Y extremes. In addition to the X and Y distances between successive extremes the model requires total stroke duration but this parameter appears to be less critical. It may be derived from the relative stroke size. More important is that, the model requires a *shape factor*, which expresses the time lag between a pair of X and Y extremes relative to the stroke duration. This shape factor determines stroke shape, ranging from counter clockwise, via straight, to clockwise. This implies that apart from the horizontal and vertical sizes of the stroke a shape factor is required which reflects the asynchrony between X and Y extremes. The shape factor could be interpreted as 'stroking sequence' information if strokes were defined in X and Y dimension separately. The conclusion is that if movements may indeed be regarded as being organized in two dimensions and if the stroking sequence is understood as the sequence of movement initiations per dimension, then the postulated movement information seems to be both parsimonious and complete.

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SUMMARY

The present thesis deals with the motor-control aspects of handwriting, i.e., with the processes and mechanisms involved in the generation and execution of handwriting movements. Chapter 1 places handwriting movements in the context of the rich variety of movements which can be performed by the human motor system. Handwriting constitutes a type of movement that on the one hand is ecologically relevant, while on the other hand it is probably less complex than many other types of every-day movement such as speaking, walking, throwing, etc. The notion of reduced complexity is based on the observations that the handwriting trajectory is defined in the spatial domain rather than in the temporal domain and that little internal or external feedback is required (because fluent handwriting is fast and overlearned). A macroscopic model of reading/speaking and spelling/writing is adopted to embed the handwriting motor-control system in the larger context of human language-processing behavior. The information flow in this model occurs via several routes, each of which consists of various sequential components or levels. Also in the more specific handwriting motor-control model, which is employed in the present thesis, a number of levels is discerned. The highest-order level investigated here, concerns the question of the specific type of movement information most likely to be stored in a long-term graphic motor memory (See Chapter 2). If the notion of a long-term memory is correct, another level is required from which the appropriate movement information is retrieved. The next question that arises here, involves the most likely size of the units of movement retrieved from this long-term memory. Is the unit a single stroke or a complete character (See Chapter 3)? Various processing levels must, moreover, be presumed for the translation of the abstract, stored movement information into more and more concrete movement information. At a certain level, the motor system has to deal with highly concrete information regarding the biomechanical properties of the arm-wrist-finger system. Because this handwriting apparatus has no symmetries, it is to be expected that the biomechanical properties will, to a certain extent, depend upon the direction of the movement (See Chapter 4). Finally, the writing pen produces a visible writing trace. However, this result is still too abstract for

direct analysis in the present type of graphonomic research. In this research context, the movement of the pen tip needs to be recorded, by means of a digitizer, and to be processed (See Chapter 5). The above-mentioned processing levels thus show a clear correspondence to the arrangement of the following chapters in the present thesis. They run from an abstract, high-level description down to a concrete, low-level description. The chapters will be discussed here briefly.

Chapter 2 deals with the question of what kind of movement information is most likely to be stored in the long-term motor memory. It is assumed that the permanently stored information manifests itself as invariant features in the ultimate movement pattern. However, specific invariant features may be the result of various factors. Therefore, if such invariant features are discovered in handwriting patterns, they do not necessarily stem from permanently stored information. In order to identify features that could stem from the stored movement information, invariances must be compared with related invariances. In this chapter, the simplest equation of movement is employed, containing only three factors: Stroke *size* is proportional to the product of stroke *duration* squared and *force* level. Each factor may show a specific invariance across replications with respect to its intended modulation across the writing pattern (i.e., signal-to-noise ratio). It appears that the stroke sizes yield a higher signal-to-noise ratio than the two other factors mentioned. In fact, its signal-to-noise ratio is higher because variations in stroke duration appear to be partly compensated by opposing variations in the same stroke's force level. This result has been obtained under optimal replication conditions. However, if writing patterns are performed in different sizes or durations, it is to be expected that the same abstract, stored movement information serves as the source information. Indeed, the stroke sizes appear to be transformed more linearly than the other two factors. These observations support the notion that the stroke-size ratios constitute an essential aspect of the handwriting-movement information stored in a long-term motor memory.

In *Chapter 3* it is assumed that, if a long-term memory for motor patterns exists, a processing level must also exist at which the appropriate units of movement information are retrieved from this long-term memory. It is of interest to know the extent of the units of movement information that are retrieved. The extent of the units could be as small as a single stroke or it could be a complete character consisting of several strokes. How can an empirical distinction be made between these alternatives? It is assumed on firm empirical grounds that retrieval processes take measurable amounts of time. As a memory-retrieval process takes place for each new unit that has to be written, it will mainly affect the duration between the moment the subject receives information about which characters to write and the moment the subject actually starts writing (i.e., choice-reaction time). In this chapter it has been shown that pairs of identical characters yield shorter choice-reaction times than pairs of different characters, regardless whether they consist of similar strokes or nonsimilar strokes. If each stroke were retrieved separately, one would expect that it would not matter whether similar strokes are arranged according to identically-shaped characters or differently-shaped characters. These results are thus in agreement with the notion that complete characters, rather than sequences of strokes, are retrieved as units from the long-term motor memory.

At which moment is the motor information retrieved from the long-term motor memory? Is it retrieved immediately after the subject is informed about the characters to be written, or is it retrieved just prior to movement execution? The answer comes from a different task presentation in the same experiment. In this task, the subject receives information about which characters to write, but is not allowed to start writing. Instead, the subject must start writing immediately following a simple 'go' signal, which is presented after a delay. The time lapse between the moment the subject receives this 'go' signal and the moment the subject actually starts writing is measured (i.e., simple-reaction time). It appears that the subjects were able to retrieve the entire movement information from the long-term memory well before the 'go' signal. The previously-mentioned differences in reaction time between various types of handwriting patterns have now disappeared. Moreover, the retrieved movement information must be stored temporarily in a short-term buffer until it is again retrieved immediately prior to execution of the movement. As the buffer-retrieval process delivers the units during movement execution, it will affect movement duration. Indeed, it appeared that sequences consisting of identical characters are executed at another rate than sequences consisting of different characters, regardless whether they consist of similar strokes or dissimilar strokes. The latter results are again compatible with complete characters rather than sequences of strokes being retrieved as units, this time from the short-term buffer.

In *Chapter 4* the biomechanics of the handwriting apparatus under restricted degrees of freedom are studied. Only wrist-joint and finger-joint movements were allowed as otherwise the system would be too complex for the intended, detailed level of description, especially regarding the large inter-individual differences in arm movements during handwriting. The wrist-joint movements appear to allow fast movements with little spatial error (with respect to a straight line). It is suggested that this joint allows such accurate trajectories because it possesses only one degree of freedom (i.e, back-and-forth movements on the paper). Movements using primarily finger joints appear to be slow. Furthermore, finger-joint movements show larger spatial errors, probably because the system of finger joints possesses at least two degrees of freedom, when producing small movements in the two-dimensional plane. This has been established with a writing task where the subjects produced back-and-forth movements in all directions. It was assumed that those movement directions that could be executed most rapidly must be the ones using the wrist joint and that those directions permitting the slowest movements must be the ones using only the finger joints. It is suggested that the properties of the handwriting apparatus can be described by two main axes having different properties and being approximately orthogonal. Movements in intermediate directions consequently require the coordination of wrist-joint movements and finger-joint movements. It appeared that movements in these intermediate directions show the largest spatial errors, which is to be expected because they possess at least three degrees of freedom. Although the properties of the handwriting apparatus are so specific for each axis, no systematic differences between the main axes could be established concerning the moments of the movement initiation or the shape of the force-versus-time curve. It seems, therefore, that the internal representation of handwriting movements is probably not in terms of these two main axes. In agreement with this is that main axes do not appear to correspond to the base-line or the slant of writing.

In *Chapter 5* movement recording and data processing are studied. The concrete and measurable movement is the movement of the pen tip as recorded by means of a digitizer. In this chapter, the average of a large number of absolute frequency spectra of the velocity has been estimated. The average spectrum shows predominant oscillations of about 5 Hz, which implies that every 1/5 second at least two X and Y coordinates (not necessarily taken simultaneously) are needed to reconstruct the writing pattern in space and time. These points could well be the extremes in X and Y direction of the strokes which are indeed 1/10 second apart on average. This implies on the one hand that the stroke is an independent movement entity, and on the other that the memory information postulated in Chapter 2 (e.g., the relative stroke sizes) may form the parsimonious and complete movement information required to generate the handwriting movements.

SAMENVATTING

Dit proefschrift handelt over de motorische aspecten van het schrijven, dat wil zeggen, over de vraag welke processen en mechanismen betrokken zijn bij de generatie en uitvoering van schrijfbewegingen. Hoofdstuk 1 plaatst schrijfbewegingen in de rijke variëteit van bewegingen die door het menselijke motorische systeem kunnen worden uitgevoerd. Er wordt gesteld dat schrijven bestaat uit een type beweging dat aan de ene kant ecologisch relevant is, terwijl het aan de andere kant waarschijnlijk minder complex is dan vele andere typen dagelijkse bewegingen (zoals spreken, lopen, gooien, enz.). Het idee van de verminderde complexiteit is gebaseerd op de waarneming dat het schrijfspoor is gedefinieerd in het plaatsdomein en niet in het tijdsdomein, en dat weinig interne of externe terugkoppeling vereist is omdat vloeiend handschrift snel en te over geoefend is. Een macroscopisch model over lezen/spreken en spellen/schrijven is overgenomen uit de literatuur om het schrijfmotoriek-systeem in de bredere context van menselijke taalverwerking in te passen. De informatiestroom vindt in dit model plaats via verschillende takken, terwijl elke tak uit verscheidene op elkaar volgende componenten of niveaus bestaat. Ook in het meer specifieke schrijfmotoriek-model, dat in dit proefschrift wordt gebruikt, worden een aantal niveaus onderscheiden. Het hoogste-orde niveau dat hier wordt onderzocht, betreft de vraag wat voor soort bewegingsinformatie het meest waarschijnlijk is opgeslagen in een lange-termijn motorisch geheugen (zie hoofdstuk 2). Als het idee van een lange-termijn geheugen juist is, dan is een ander niveau vereist waar de geschikte bewegingsinformatie worden opgehaald uit dit lange-termijn geheugen. Een vraag die vervolgens opkomt is wat de meest waarschijnlijke omvang is van de bewegingseenheden die worden opgehaald: Is de eenheid een enkele haal of een complete letter (zie hoofdstuk 3)? Verscheidene verwerkingsniveaus moeten bovendien worden verondersteld voor de vertaling van de abstracte, opgeslagen bewegingsinformatie in meer en meer concrete bewegingsinformatie. Op een zeker niveau heeft het motorisch systeem te maken met uiterst concrete informatie zoals de biomechanische eigenschappen van het systeem van arm, hand en vingers. Omdat dit schrijfapparaat geen symmetrieën heeft, is het te verwachten dat de biomechanische eigenschappen enigermate zullen afhangen van de bewegingsrichting (zie hoofdstuk 4). Tenslotte produceert de schrijfpen een zichtbaar schrijfspoor. Dit resultaat is echter nog te abstract voor directe analyse in het huidige type grafonomisch onderzoek. Daarom dient de beweging van de penpunt te worden geregistreerd, hetgeen geschiedt door middel van een digitizer, en vervolgens te worden verwerkt (zie hoofdstuk 5). De bovengenoemde verwerkingsniveaus vertonen aldus een duidelijke overeenkomst met de volgorde van de hoofdstukken in deze proefschrift, die lopen van een abstracte, hoog-niveau beschrijving tot een concrete laag-niveau beschrijving. De hoofdstukken worden hierna kort besproken.

Hoofdstuk 2 handelt over de vraag welk soort bewegingsinformatie het meest waarschijnlijk is opgeslagen in het lange-termijn motorische geheugen. Er wordt verondersteld dat de blijvend opgeslagen informatie zich openbaart in de vorm van invariante kenmerken in het uiteindelijke bewegingspatroon. Er zouden echter meer oorzaken kunnen zijn die kunnen leiden tot specifieke invariante kenmerken. Als zulke invariante kenmerken worden ontdekt in schrijfpatronen hoeven ze daarom niet noodzakelijkerwijs af te stammen van de blijvend opgeslagen informatie. Om kenmerken te identificeren die zouden kunnen stammen van de opgeslagen bewegingsinformatie is het nodig dat invarianties worden vergeleken met andere invarianties. In dit hoofdstuk wordt de meest eenvoudige bewegingsvergelijking gebruikt die slechts drie factoren bevat: *haal-grootte* is evenredig met het product van *haal-duur* in het kwadraat en *krachtsniveau*. Elke factor kan bij herhalingen van de uitvoering een specifieke invariantie vertonen ten opzichte van de bedoelde modulatie over het schrijfpatroon (d.w.z. de signaal-ruisverhouding). Het blijkt dat het patroon van de haalgrootten een hogere signaal-ruisverhouding oplevert dan de twee andere genoemde factoren. In feite is de signaal-ruisverhouding hoger omdat variaties in haalduur gedeeltelijk blijken te worden gecompenseerd door tegengestelde variaties van het krachtsniveau van dezelfde haal. Dit resultaat is verkregen onder optimale herhalingscondities. Maar ook als schrijfpatronen worden uitgevoerd met verschillende schrijfgrootten of -snelheden is het te verwachten dat dezelfde abstracte, opgeslagen bewegingsinformatie blijft dienen als broninformatie. De haalgrootten blijken inderdaad meer linear te worden getransformeerd dan de twee andere factoren. Deze observaties ondersteunen de opvatting dat de haalgrootteverhoudingen een essentieel deel vormen van de informatie die ligt opgeslagen in een lange-termijn motorisch geheugen.

In *hoofdstuk 3* wordt aangenomen dat indien er een lange-termijn geheugen voor motorische patronen bestaat, er ook een verwerkingsniveau moet bestaan waar de geschikte bewegingsinformatie wordt opgehaald uit dit lange-termijn geheugen. Het is nu van theoretisch belang de omvang te kennen van de eenheden van bewegingsinformatie die worden opgehaald. De omvang van de eenheden van schrijfpatronen zou slechts een enkele haal kunnen zijn, maar ook een hele letter bestaande uit verscheidene halen. Hoe kan een empirisch onderscheid gemaakt worden tussen deze alternatieven? Op harde empirische gronden wordt aangenomen dat ophaalprocessen meetbare hoeveelheden tijd kosten. Omdat een geheugen-ophaalproces plaats vindt vóór elke nieuwe eenheid die geschreven moet worden, zal het hoofdzakelijk de duur beïnvloeden tussen het moment dat de proefpersoon informatie krijgt over welke letters geschreven moeten worden en het moment dat de proefpersoon werkelijk begint te schrijven (d.w.z. de keuzereactietijd). In dit hoofdstuk wordt gedemonstreerd dat paren van identieke letters kortere keuzereaktietijden opleveren dan paren van verschillende letters, onverschillig of ze uit gelijkvormige halen of uit niet-gelijkvormige halen bestaan. Als elke haal afzonderlijk zou worden opgehaald, zou men verwachten dat het niets uit zou maken of gelijkvormige halen zijn gerangschikt volgens identiek gevormde letters of uit verschillend gevormde letters. Deze resultaten zijn dus in overeenstemming met de opvatting dat complete letters en niet afzonderlijke halen worden opgehaald uit het lange-termijn motorische geheugen.

Op welk moment wordt de motorische informatie opgehaald uit het lange-termijn geheugen? Wordt deze opgehaald onmiddellijk na het moment waarop de proefpersoon informatie krijgt over de letters die moeten worden geschreven, of juist vóór het moment van bewegingsuitvoering? Het antwoord wordt geleverd door hetzelfde experiment maar dan met een andere taakaanbieding. Eerst krijgt de proefpersoon informatie over de letters die geschreven moeten worden, maar men mag nog niet beginnen te schrijven. In plaats daarvan moet de proefpersoon onmiddellijk na een enkelvoudig startsignaal, dat enige tijd later volgt, beginnen te schrijven. De tijd tussen het moment dat de proefpersoon dit signaal krijgt en het moment dat de proefpersoon werkelijk begint te schrijven is gemeten (d.w.z. enkelvoudige reactietijd). Het blijkt dat de proefpersonen in staat waren de gehele bewegingsinformatie uit het lange-termijn geheugen op te halen ruim op tijd vóór het startsignaal: De bovengenoemde verschillen in reactietijd zijn nu verdwenen. Bovendien moet de opgehaalde bewegingsinformatie tijdelijk worden opgeslagen in een korte-termijn buffer totdat het nogmaals opgehaald wordt onmiddellijk vóór de uitvoering van de beweging. Omdat het buffer-ophaalproces de eenheden levert tijdens de bewegingsuitvoering, zal het de bewegingsduur beïvloeden. Het bleek inderdaad dat reeksen bestaande uit identieke letters in een lager tempo worden uitgevoerd dan de reeksen bestaande uit verschillende letters, onverschillig of ze bestaan uit gelijkvormige of niet-gelijkvormige halen. De laatste resultaten zijn weer in overeenstemming met de opvatting dat complete letters en niet reeksen van halen worden opgehaald, nu uit het korte-termijn buffer.

In *hoofdstuk 4* wordt de biomechanica van het schrijfapparaat bestudeerd onder condities waarin het aantal vrijheidsgraden wordt beperkt: Slechts polsgewrichts- en vingergewrichts-bewegingen waren toegestaan omdat anders het systeem te complex zou zijn voor het bedoelde, gedetailleerde niveau van beschrijving, vooral vanwege de grote inter-individuele verschillen van de armbewegingen bij het schrijven. De polsgewrichts-bewegingen blijken snel te kunnen worden uitgevoerd met een geringe ruimtelijke fout (ten opzichte van een rechte lijn). Er is geopperd dat dit gewricht zulke nauwkeurige trajecten mogelijk maakt omdat het slechts één vrijheidsgraad bezit (namelijk, heen-en-weerbewegingen op het paper). Bewegingen die hoofdzakelijk de vingergewrichten gebruiken, blijken slechts langzaam te kunnen worden uitgevoerd. Verder vertonen vingergewrichts-bewegingen grotere ruimtelijke fouten, waarschijnlijk omdat het systeem van vingergewrichten bij kleine bewegingen in het tweedimensionale vlak minstens twee vrijheidsgraden bezit. Dit is vastgesteld met een schrijftaak waarbij de proefpersonen heen-en-weerbewegingen in alle richtingen produceerden. Er wordt aangenomen dat richtingen die de snelste bewegingen toelieten die richtingen zijn waarbij het polsgewricht wordt gebruikt en dat richtingen die de minst snelle bewegingen toestonden die zijn waarbij alleen vingergewrichten gebruikt worden. Er wordt geopperd dat de eigenschappen van het schrijfapparaat kunnen worden beschreven door twee hoofdassen die verschillende eigenschappen hebben en die bij benadering orthogonaal zijn. Bewegingen in tussenliggende richtingen impliceren derhalve de coördinatie van de polsgewrichts- en vinger-gewrichtsbewegingen. Het blijkt inderdaad dat bewegingen in deze tussenliggende richtingen de grootste ruimtelijke fout vertonen, wat te verwachten was omdat ze ten minste drie vrijheidsgraden bezitten. Hoewel de eigenschappen van het schrijfapparaat voor elk van de twee assen zo specifiek zijn, konden er geen systematische verschillen tussen de hoofdassen worden vastgesteld wat betreft de momenten van de bewegingsinzet of de vorm van de kracht-versus-tijd curve. Het schijnt derhalve dat de interne representatie van schrijfbewegingen waarschijnlijk niet in termen van deze twee hoofdassen is. In overeenstemming hiermee is dat hoofdassen niet blijken te korresponderen met de basislijn of de helling van het handschrift.

In *hoofdstuk 5* worden de registratie en de dataverwerking van schrijfbewegingen bestudeerd. De concrete en meetbare beweging is de beweging van de penpunt zoals die geregistreerd wordt met behulp van een digitizer. In dit hoofdstuk is het gemiddelde van een groot aantal absolute frequentiespectra van de snelheid geschat. Het gemiddelde spectrum toont een overheersende oscillatie bij ongeveer 5 Hz, wat impliceert dat elke 1/5 seconde minstens twee X en Y coordinaten (niet noodzaklijk op hetzelfde moment) nodig zijn om het schrijfpatroon te reconstrueren in plaats en tijd. Die punten zouden goed de extrema in X en Y richting van de halen kunnen zijn, die inderdaad gemiddeld 1/10 seconde gescheiden zijn. Dit impliceert enerzijds dat de haal een onafhankelijke bewegingseenheid is en anderzijds dat de geheugeninformatie als gepostuleerd in hoofdstuk 2 (o.a. de relatieve haalgroottes) de zuinige en volledige bewegingsinformatie kunnen vormen, die vereist is voor de generatie van schrijfbewegingen.

Curriculum Vitae

Johannes Leonardus Hermanus Maria Teulings (Hans-Leo) werd geboren op 7 maart 1952 in Steenbergen. Vanaf september 1965 bezocht hij de middelbare school (HBS-B, Canisius College, Nijmegen). Vanaf september 1970 studeerde hij natuurkunde aan de Katholieke Universiteit Nijmegen. In februari 1976 behaalde hij het doctoraal examen Experimentele Natuurkunde, met als afstudeerrichting Biofysica. Sinds juli 1976 is hij werkzaam aan de vakgroep Psychologische Functieleer van de Katholieke Universiteit Nijmegen. Tot september 1980 was hij werkzaam op een door de Universitaire Onderzoekspool gesubsidicerd onderzoek getiteld "Motorische voorwaarden voor het schrijven". Vanaf december 1980 tot maart 1981 participeerde hij aan een onderzoek van Prof. N. Søvik, Universiteit Trondheim, Noorwegen, naar training en beoordeling van schrijfbewegingen bij kinderen. Van maart 1981 tot maart 1984 was hij werkzaam op een door de stichting voor Zuiver Wetenschappelijk Onderzoek gesubsidieerd project getiteld "Psychomotorische aspecten van het schrijven". In 1982 organiseerden Prof. A.J.W.M. Thomassen en hij de eerste "International Workshop on Handwriting". Van december 1984 tot heden vervult hij de rol van area manager voor een door ESPRIT gesubsidieerd onderzoek "Cursive-script analysis" binnen het Europese consortium "Image and Movement Understanding" (Project 419).

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STELLINGEN

Handwriting-movement control: Research into different levels of the motor system, Hans-Leo Teulings, 26 april 1988.

Stellingen

1. Het toeschrijven van invariantie aan een kenmerk van bewegingspatronen kan misleidend zijn indien de mate van invariantie niet vergeleken is met die van gerelateerde kenmerken. *Dit proefschrift.*

2. De dertig jaar geleden geopperde veronderstelling dat het automatisch herkennen van verbonden handschrift kan dienen als een voorstudie voor automatische spraakherkenning berust op een misverstand. *Zie N. Lindgren (1965). Machine recognition of human language, Part III: Cursive-script recognition. IEEE Spectrum, 2, 104-116.*

3. Automatische handschriftherkenning vereist kennis van de schrijfbeweging.

4. De algehele ontspanning die het beoefenen van Chinese calligrafie blijkt te bewerkstelligen, verdient ook bij andere schrijfvormen te worden bestudeerd en bij een positief resultaat te worden toegepast in therapeutische situaties. *Kao et al. (1988). Physiological changes associated with Chinese calligraphy. In R. Plamondon et al. (Eds.), Computer recognition and human production of handwriting. Singapore: World Scientific Publishing Co.*

5. De kloof tussen de fysiologische en de psychologische benadering van de motoriek kan worden overbrugd door de microscopische eigenschappen van zenuwcellen toe te passen in wiskundige modellen voor macroscopisch meetbare bewegingen. Zo leidt het bestaan van zenuwcellen die naar de tijd kunnen differentiëren, in combinatie met wiskundige Taylorreeksen tot de hypothese dat een systeem van deze zenuwcellen anticiperend gedrag kan vertonen. *A. Pellionisz & R. Llinás (1979). Brain modeling by tensor network theory and computer simulation. The cerebellum: Distributed processor for predictive coordination. Neuroscience, 4, 323-348.*

6. De paradoxale resultaten van Sittig (1986) met betrekking tot de *Vibration-Induced Discrepancy* komen in een ander daglicht te staan als kan worden aangetoond dat het effect van vibratie groter is op een ontspannen pees dan op een door armbeweging gespannen pees. *Sittig, A.C. (1986). Kinesthesis and motor control. Proefschrift, Universiteit Utrecht.*

7. Bij *Desk Top Publishing* komt het er minder op aan dat de gebruiker alle mogelijkheden van het systeem benut dan dat deze de moeilijker te beheersen regels betreffende overzichtelijkheid en leesbaarheid hanteert.

8. Het verdient aanbeveling geen beslissingen te nemen op basis van een meerderheid van stemmen die zo gering is dat deze ook bereikt had kunnen worden indien iedere stem door het toeval bepaald was.

9. Dat nog steeds niets gedaan wordt aan de onderdrukking van de 15 kHz pieptoon van televisietoestellen wijst erop dat de personen die daarover beslissen door hun leeftijd dergelijke tonen niet meer kunnen horen.

10. Milieubewust autorijden vereist niet alleen matige acceleratie, maar ook een matig gebruik van het rempedaal omdat dit laatste de energie, die reeds vervuiling veroorzaakt heeft, teniet doet en bovendien asbest in de atmosfeer brengt.